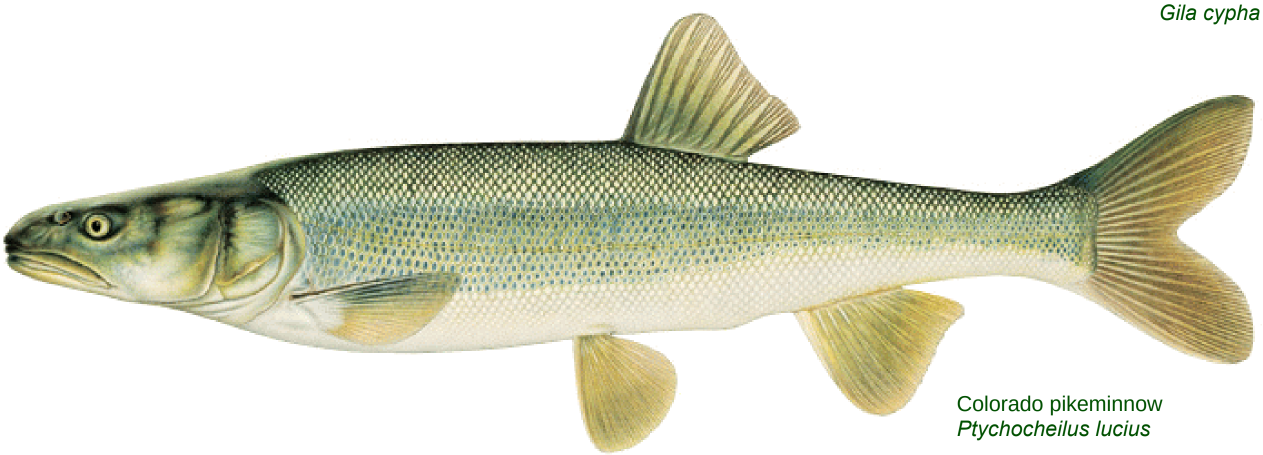
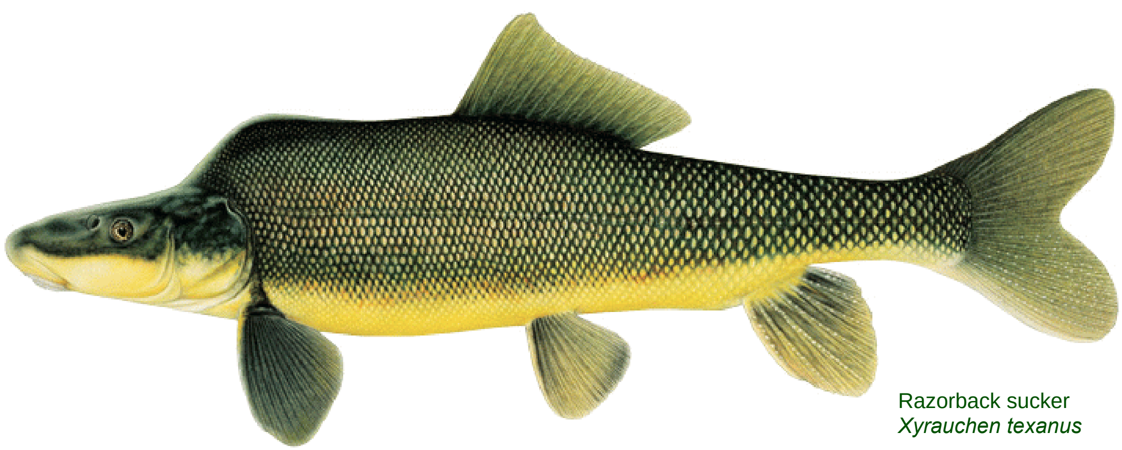
Flow and Temperature Recommendations for Endangered Fishes in the Green River Downstream of Flaming Gorge Dam

Humpback chub
Gila cypha



Colorado pikeminnow
Ptychocheilus lucius



Razorback sucker
Xyrauchen texanus

Upper Colorado River
Endangered Fish Recovery Program
Project FG-53

Final Report
September 2000

FLOW AND TEMPERATURE RECOMMENDATIONS FOR ENDANGERED FISHES IN THE GREEN RIVER DOWNSTREAM OF FLAMING GORGE DAM

prepared by

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Final Report

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Chapter 1: Introduction	John W. Hayse, Kirk E. LaGory
Chapter 2: Flaming Gorge Flow Recommendations Investigation	John W. Hayse, Robert T. Muth, Kirk E. LaGory, Larry W. Crist
Chapter 3: Hydrology and Geomorphology of the Green River	Joseph K. Lyons, Kirk E. LaGory, Thomas P. Ryan
Chapter 4: Fishes of the Green River	
4.1 Overview	Robert T. Muth
4.2 Colorado Pikeminnow	Kevin R. Bestgen
4.3 Razorback Sucker	Robert T. Muth
4.4 Humpback Chub	Larry W. Crist, Richard A. Valdez
Chapter 5: Flow and Temperature Recommendations	Robert T. Muth, Larry W. Crist, Kirk E. LaGory, Kevin R. Bestgen, Thomas P. Ryan, John W. Hayse
Appendix A: Supporting Information on the Hydrology of the Green River System	Thomas P. Ryan, Kirk E. LaGory

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NOTATION

Abbreviations

Biological Opinion	1992 Biological Opinion on Operation of Flaming Gorge Dam
CPUE	catch per unit effort
CRSS	Colorado River Simulation System
CV	coefficient of variation
EIS	environmental impact statement
HDB	(Upper Colorado) hydrologic database
Integration Team	Flaming Gorge Technical Integration Team
ISMP	Interagency Standardized Monitoring Program
NWR	National Wildlife Refuge
RIPRAP	Recovery Implementation Program Recovery Action Plan
RK	river kilometer(s), measured as kilometers upstream of Green and Colorado River confluence
Reclamation	U.S. Bureau of Reclamation
Recovery Program	Upper Colorado River Endangered Fish Recovery Program
Service	U.S. Fish and Wildlife Service
TL	total length of fish (i.e., tip of snout to most posterior margin of caudal fin)
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
Western	Western Area Power Administration
YOY	young-of-year

Units of Measure

°C	degree(s) Celsius
cfs	cubic foot (feet) per second
cm	centimeter(s)
d	day(s)
h	hour(s)
ha	hectare(s)
kg	kilogram(s)
km	kilometer(s)
km^2	square kilometer(s)
L	liter(s)
μm	micrometer(s)
m	meter(s)
m^2	square meter(s)
m^3	cubic meter(s)
mm	millimeter(s)
s	second(s)

Conversions

$^oC = 5/9\ (^oF - 32)$

$^oF = 9/5\ (^oC) + 32$

m = feet × 0.3048

m^3 = acre-feet × 1233.5

m^3/s = cfs × 0.028317

cfs = m^3/s × 35.314

RK = river mile × 1.609

river mile = RK × 0.6215

Equivalents Tables

Temperature

ºF	ºC
32	0
40	4.4
50	10.0
60	15.6
70	21.1
80	26.7

Flow

cfs	m^3/s
800	22.7
1,000	28.3
2,000	56.6
3,000	85.0
4,000	113.3
4,600	130.3
5,000	141.6
7,500	212.4
10,000	283.2
15,000	424.8
20,000	566.3
25,000	707.9
30,000	849.5
40,000	1,132.7

Locations of Key Features along the Green River

Feature	Distance Upstream from Confluence with Colorado River (km)	Distance Downstream from Flaming Gorge Dam (km)
Flaming Gorge Dam	659.8	0
USGS Greendale gage	659.0	0.8
Gates of Lodore	583.3	76.5
Yampa River confluence	555.1	104.7
USGS Jensen gage	509.5	150.3
White River confluence	396.2	263.6
USGS Green River gage	192.7	467.1
San Rafael River confluence	156.2	503.6
Colorado River confluence	0	659.8

EXECUTIVE SUMMARY

The Green River system of the upper Colorado River basin in Utah and Colorado supports populations of three endangered fishes — humpback chub *Gila cypha*, Colorado pikeminnow *Ptychocheilus lucius*, and razorback sucker *Xyrauchen texanus* — and it historically supported the endangered bonytail *Gila elegans*. Bonytails are almost unknown in recent collections. Razorback suckers are extremely rare and continue to decline. Humpback chubs and Colorado pikeminnow still reproduce and recruit in the Green River system, but their long-term viability in the system is uncertain. Systemwide reductions in spatial and temporal components of habitat complexity, attributed to past and ongoing alterations in river flow and temperature, have been implicated as major factors contributing to the decline of all the endangered fishes.

Operation of Flaming Gorge Dam, which is located on the upper main-stem Green River, strongly influences downstream flow and temperature regimes and the ecology of riverine biota, including native fishes. The U.S. Fish and Wildlife Service (Service), in its 1992 Biological Opinion on Operation of Flaming Gorge Dam (Biological Opinion), concluded that continuation of historic operations at Flaming Gorge Dam was likely to further reduce the distribution and abundance of these federally protected species and thus jeopardize their continued existence. The Biological Opinion identified a reasonable and prudent alternative containing several related elements. These elements included (1) refine the operation of Flaming Gorge Dam so that flow and temperature regimes more closely approximate historic conditions; (2) conduct a 5-year research program ("Flaming Gorge Flow Recommendations Investigation") to include implementation of winter and spring "research flows" beginning in 1992, to allow for potential refinement of flows for those seasons; (3) determine the feasibility and effects of releasing warmer water during the late spring through summer period and investigate the feasibility of retrofitting river bypass tubes to include power generation capability, thereby facilitating higher spring releases; (4) legally protect Green River flows from Flaming Gorge Dam to Lake Powell; and (5) initiate discussions with the Service after conclusion of the Flaming Gorge Flow Recommendations Investigation to examine further refinement of flows and temperatures for the endangered fishes.

The Flaming Gorge Flow Recommendations Investigation, which began in 1992 but also included research conducted in 1990 and 1991 (while the Biological Opinion was being prepared), was conducted under the auspices of the Upper Colorado River Endangered Fish Recovery Program. The purpose of the investigation was to evaluate and refine the original flow and temperature recommendations given in the Biological Opinion as part of the reasonable and prudent alternative. Specifically, the Flaming Gorge Flow Recommendations Investigation was intended to determine the biological and physical responses of the Green River system to seasonal flow modifications, develop data for refinement of flow recommendations, and investigate the potential effects of increasing the temperature of water released from Flaming Gorge Dam. Specific objectives of the investigation were to (1) track reproduction of the endangered fishes and determine relationships among seasonal flows, water temperatures, and reproductive success; (2) evaluate recruitment of the endangered fishes from age-0 to subsequent life-history stages and determine relationships among seasonal flows, water temperatures, and survival of young fish; (3) monitor the relative abundance and population structure of the endangered fishes in order to acquire information on interactions among fish species and how flows may differentially affect populations; and (4) determine how releases from Flaming Gorge Dam and flows from tributaries affect the formation and maintenance of important habitats for the endangered fishes throughout the Green River. To accomplish these objectives, a series of long-term studies was conducted to track changes in populations, reproductive success, and habitats. In addition, shorter-duration studies were conducted to examine specific hypotheses and flow relationships. This report summarizes and synthesizes the results of the Flaming Gorge Flow Recommendations Investigation as well as other relevant information to provide recommended flow and temperature regimes that would benefit the endangered fishes in the Green River.

The study area for the investigation encompassed the main-stem Green River from Flaming Gorge Dam downstream to its confluence with the Colorado River, including relevant portions of major tributaries. The Green River was divided into three contiguous reaches delimited by major tributaries: Reach 1 — Flaming Gorge Dam to the Yampa River confluence (river kilometer [RK] 555.1 to 659.8), Reach 2 — Yampa River confluence to the White River confluence (RK 396.2 to 555.1), and Reach 3 — White River confluence to the Colorado River confluence (RK 0.0 to 396.2).

Data gathered during the Flaming Gorge Flow Recommendations Investigation and other studies were used to develop descriptions of the basic life history, habitat use, and population status of the Colorado pikeminnow, razorback sucker, and humpback chub in the Green River system downstream of Flaming Gorge Dam. This information is summarized below.

The Colorado pikeminnow is widespread in the Green River system and occurs in both the mainstem and tributaries. The largest numbers of adults are found in Green River Reaches 2 and 3, particularly downstream of Jensen, Utah, but adults also occur in Lodore Canyon of lower Reach 1 and in upper Reach 2. Adult Colorado pikeminnow migrate to spawning areas in the lower Yampa River and the Green River in Reach 3 in late spring, and they spawn there in summer. Larvae emerge from spawning substrates and are swept downstream to nursery-habitat areas, primarily downstream of Jensen. Reproduction by Colorado pikeminnow occurred in all years of study, but both the production of larvae and the recruitment of age-0 juveniles in autumn were highly variable among years. Because the main-stem Green River supports all early life stages and large numbers of adults, it is considered essential for recovery of the Colorado pikeminnow.

High spring flows benefit Colorado pikeminnow because these flows maintain the in-channel habitats used by all life stages of the fish and because they inundate floodplain habitats that provide warm, food-rich environments important for the growth, rest, and conditioning of juvenile, subadult, and adult fish. The patterns of spring flow and water temperature provide the fish with cues to begin spawning migrations and reproduction. Elevation of reworked in-channel sediment deposits is set by the magnitude of the spring peak and declining post-peak flows. During summer and autumn base flows, nursery habitats form in low-velocity areas associated with sediment deposits. Conditions in the nursery habitats during this period are critical for growth and survival of age-0 Colorado pikeminnow.

The Green River system supports the largest remaining riverine population of razorback suckers. However, recruitment is insufficient, and their population is declining to precariously low levels. Lack of recruitment is attributed primarily to low production of larvae and high mortality of early life stages. Floodplain habitats, which are important for all life stages of the razorback sucker, are critical for survival of early life stages because they provide warm, food-rich environments. Restoring access to inundated floodplain habitats appears to be crucial for the recovery of the razorback sucker. Spring peaks of sufficient frequency, magnitude, and duration to inundate floodplain habitats are needed to enhance growth and survival of young razorback suckers.

Reproduction and recruitment of humpback chubs occur in Desolation and Gray Canyons in Reach 3. A few humpback chubs occur in Whirlpool and Split Mountain Canyons of upper Reach 2, but the current abundance and life history of chubs in those areas are unknown. High spring flows prepare spawning habitats and provide the fish with cues for spawning, which occurs as runoff declines in late spring. Young fish inhabit low-velocity shorelines and backwater habitats as flow decreases during summer. Older juveniles inhabit deeper offshore eddies, often in association with boulders or other cover. Large eddies form at high flow and provide habitat in which humpback chubs spawn and feed on entrained allochthonous materials. Complex shoreline habitats used by larvae and juveniles are available at relatively low base flows during summer and autumn.

Information on each endangered fish species was used to develop integrated flow and temperature recommendations for the Green River downstream of Flaming Gorge Dam. The goal of the recommendations is to provide the annual and seasonal flow and temperature patterns in the Green River that would enhance populations of the endangered fishes. Six objectives were developed to achieve this goal: (1) provide appropriate conditions that allow gonadal maturation and environmental cues for spawning movements and reproduction; (2) form low-velocity habitats for pre-spawning staging and post-spawning feeding and resting areas; (3) inundate floodplains and other off-channel habitats at the appropriate time and for an adequate duration to provide warm, food-rich environments for fish growth and conditioning and to provide river-floodplain connections for the restoration of natural ecosystem processes; (4) restore and maintain the channel complexity and dynamics needed for the formation and maintenance of high-quality spawning, nursery, and adult habitats; (5) provide base flows that promote favorable conditions in low-velocity habitats during summer, autumn, and winter; and (6) minimize differences in water temperature between the Green River and Yampa River in Echo Park to prevent temperature shock and possible mortality to larval Colorado pikeminnow transported from the Yampa River and into the Green River during summer.

To achieve these objectives, Flaming Gorge Dam releases should provide a wide range of peak and base flows, and daily fluctuations in downstream reaches due to hydropower generation should be moderated. Providing greater inter-annual flow variability would maintain and restore important geomorphic and biological processes and improve the spatial and temporal habitat complexity in the system, which is required by the endangered fishes. Such inter-annual variability should be achieved by providing flows consistent with hydrologic conditions in the upper Green River basin in a given year. Flow recommendations were based on the following information or assumptions: (1) populations of the endangered fishes and habitats required by all life stages are concentrated in Reaches 2 and 3 of the Green River; (2) habitat for endangered fishes in Reach 1 is limited to Lodore Canyon because the summer water temperatures upstream are too cold; (3) providing suitable habitat conditions through flow and temperature management at Flaming Gorge Dam will enhance endangered fish populations in the Green River; (4) current hydrology of the upper Green River basin, including inflows to Flaming Gorge Reservoir and available release volumes from Flaming Gorge Dam, will remain largely unaltered; and (5) changes in flow, temperature, and sediment regimes in Green River tributaries (particularly the Yampa and White Rivers) will be consistent with known or pending biological opinions.

Specific peak- and base-flow target levels are recommended for each reach for five hydrologic conditions as defined by exceedance probability: wet (0–10% exceedance), moderately wet (10–30% exceedance), average (30–70% exceedance), moderately dry (70–90% exceedance), and dry (90–100% exceedance). Over the full range of hydrologic conditions, recommended peak releases from Flaming Gorge Dam range from full power-plant capacity (130 m^3/s [4,600 cubic feet per second or cfs]) to greater than full bypass (244 m^3/s [8,600 cfs]) as needed to achieve specific target flows in Reaches 2 and 3. No upper limits are placed on recommended peak-flow releases in any hydrologic condition. Onset of peak dam releases should be timed to coincide with peak and immediate post-peak spring flows in the Yampa River to produce higher peak flows and extend the duration of peak flows. Recommended peak flows in Reach 2 range from 235 m^3/s (8,300 cfs) in dry years to greater than 748 m^3/s (26,400 cfs) in wet years. In Reach 3, recommended peak flows range from 235 m^3/s (8,300 cfs) in dry years to greater than 1,104 m^3/s (39,000 cfs) in wet years.

Relatively low base flows should be maintained for the summer through winter period (August through February). Base-flow releases from Flaming Gorge Dam should be based on the year's hydrologic condition (23–28 m^3/s [800–1,000 cfs] in dry years to 50–76 m^3/s [1,800–2,700 cfs] in wet years). Recommended annual mean base flows for Reach 2 range from 26–31 m^3/s (900–1,100 cfs) in dry years to 79–85 m^3/s (2,800–3,000 cfs) in wet years and, for Reach 3, they range from 38–72 m^3/s (1,300–2,600 cfs) in dry years to 92–133 m^3/s (3,200–4,700 cfs) in wet years. Variation in flow around the annual mean base flow for Reach 2 should be consistent with the variability that occurred in pre-dam flows. Mean daily flows should be kept within ± 40% of the annual mean base flow in summer–autumn (August through November) and within ± 25% of the annual mean base flow in winter (December through February); however, dam operations should not be adjusted to compensate for short-term increases in tributary inflow resulting from weather events that would exceed these thresholds.

Differences in mean daily flows between consecutive days caused by reservoir operations should not exceed 3%. Flow variations resulting from hydropower generation at Flaming Gorge Dam should be limited to produce stage changes of no more than 0.1 m within a day at the U.S. Geological Survey (USGS) gage near Jensen, Utah.

Wet (0–10% exceedance) and moderately wet (10–30% exceedance) years were identified as being critical for razorback sucker recruitment in Reach 2 because the recommended peak flows in those years would be high enough to provide the substantial floodplain inundation that is critical to the growth and survival of larval and age-0 fish. Inundation of floodplain habitats would also provide growth and conditioning habitats for other species and restore certain ecosystem functions dependent on river-floodplain connections. Although Colorado pikeminnow and humpback chub habitats are rejuvenated by the very high spring flows of wetter years, production of young and recruitment are expected to be higher in moderate- and lower-flow years. The frequency of floodplain inundation could be increased (and thus greater levels of inundation achieved in average years) by removing or altering existing levees in Reaches 2 and 3.

Temperature conditions for endangered fishes could be improved by releasing relatively warm water from Flaming Gorge Reservoir (up to 15°C) and through flow management. Water temperatures of 18–20°C should be targeted for 2 to 5 weeks in summer and autumn in Lodore Canyon of lower Reach 1. Warmer water would increase the potential for Colorado pikeminnow and humpback chubs to reproduce in this portion of the river and would improve conditions for endangered fishes in upper Reach 2. The possibility of cold shock to Colorado pikeminnow larvae as they drift from the warmer Yampa River and into the colder Green River should be minimized by targeting Green River temperatures that are no more than 5°C colder than the Yampa River during the period of drift.

Additional research and monitoring is necessary to resolve uncertainties and refine the flow and temperature recommendations. Although it is beyond the scope of this report to provide a comprehensive list of research and monitoring topics, additional data collection should focus on evaluating and modifying the flow and temperature recommendations by using an adaptive-management approach. Specific experiments based on hypothesis testing should be conducted to refine recommendations on base-flow variability. Long-term monitoring should be implemented that focuses on reachwide population responses of the endangered fishes and other native and nonnative fishes to the flow and temperature recommendations. The greatest benefit will be accrued if flow and temperature recommendations are based on the observed biological response of target populations and other relevant ecological factors.

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1 INTRODUCTION

The Green River system of the upper Colorado River basin in Utah and Colorado supports populations of three endangered fishes — humpback chub *Gila cypha*, Colorado pikeminnow[1] *Ptychocheilus lucius*, and razorback sucker *Xyrauchen texanus* — and it historically supported the endangered bonytail *Gila elegans* (U.S. Fish and Wildlife Service [USFWS] 1994). Specifically, the system has two of the remaining six populations of humpback chub (USFWS 1990a; Valdez and Ryel 1995, 1997), the largest populations of Colorado pikeminnow (USFWS 1991a), and the largest riverine population of razorback sucker (USFWS 1998a). One of the last reported concentrations of bonytail was in the Green River within Dinosaur National Monument, and the species may still exist in the system in extremely low numbers (USFWS 1990b). Consequently, the Green River system is considered vital to recovery of these federally protected species. The Green River downstream of the Yampa River confluence and portions of the Yampa, White, and Duchesne Rivers have been designated as critical habitat under provisions of the Endangered Species Act, as amended (USFWS 1994).

> ***Endangered species*** – A species that is in danger of extinction throughout all or a significant portion of its range.
>
> ***Threatened species*** – A species that is likely to become endangered within the foreseeable future throughout all or a significant portion of its range.
>
> ***Critical habitat*** – The specific areas within a geographical area occupied by a threatened or endangered species, at the time it is listed, containing those physical or biological features essential to the conservation of the species and which may require special management considerations or protection. May also include areas outside the geographical area occupied by the species, at the time it is listed, upon determination by the Secretary of the Interior that such areas are essential for the conservation of the species.

Systemwide reductions in spatial and temporal components of habitat complexity, attributed to past and ongoing alterations in river flow and temperature, have been implicated as major factors contributing to decline of the endangered fishes (Stanford 1994). Operation of Flaming Gorge Dam, which is located on the upper main-stem Green River, strongly influences downstream flow and

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[1]Colorado pikeminnow is the currently accepted common name for *Ptychocheilus lucius*, formerly known as Colorado squawfish (Nelson et al. 1998).

temperature regimes and the ecology of riverine biota, including native fishes. Other perturbations to the Green River system include proliferation of nonnative fishes, water depletions in tributaries, construction of levees, encroachment of nonnative vegetation, and contamination of surface water and groundwater.

The 1992 Biological Opinion on Operation of Flaming Gorge Dam (Biological Opinion; USFWS 1992) concluded that dam operations jeopardized the continued existence of humpback chub, Colorado pikeminnow, and razorback sucker, and the reasonable and prudent alternative recommended changes in seasonal releases from the dam (Section 1.3). Those recommendations were based on the best available scientific information, but the Biological Opinion identified a need for additional research to better define river flow and temperature regimes that would benefit the endangered fishes. In 1990, the U.S. Fish and Wildlife Service (Service) and U.S. Bureau of Reclamation (Reclamation) submitted a proposal to the Upper Colorado River Endangered Fish Recovery Program (Recovery Program) recommending a cooperative agency approach to further study the effects of operating the Flaming Gorge Dam on endangered fishes in the Green River system. That proposal resulted in the development and implementation of the Flaming Gorge Flow Recommendations Investigation (Chapter 2).

1.1 PURPOSE AND SCOPE

The purpose of this report is to assess flow-habitat relationships of the endangered fishes and refine flow and temperature recommendations specified in the 1992 Biological Opinion. The recommendations presented in Chapter 5 are intended to address recovery elements identified by the Recovery Program. The purpose of the Recovery Program is to recover the endangered fishes while allowing existing and new water development to proceed in the upper basin. Its overall goal for recovery of the endangered fishes is to achieve naturally self-sustaining populations and to protect the habitats on which they depend. The Recovery Implementation Program Recovery Action Plan (RIPRAP) is an operational plan for implementing the recovery program within the following elements: (1) identify and protect in-stream flows, (2) restore habitat, (3) reduce negative impacts of nonnative fishes and sport-fish management activities, (4) conserve genetic integrity and augment or restore populations, (5) monitor populations and habitat and conduct research to support recovery actions, (6) increase public awareness and support for the endangered fishes and the Recovery Program, and (7) provide program planning and support.

Flow and temperature management alone may not be sufficient to ensure self-sustaining populations of the endangered fishes in the Green River. In fact, a combination of flow and nonflow management actions will probably be necessary for recovery. It is anticipated that the recommendations made in this report will not affect the ability of the Recovery Program to implement other appropriate recovery actions, and that they will facilitate the success of those actions by improving habitat conditions and enhancing the status of endangered fish populations. In addition, successful implementation of the recommendations will require consideration of both

Flaming Gorge Dam operations and the flow contributions from tributaries. Of particular importance is the Yampa River, the largest tributary of the Green River.

This report focuses on Colorado pikeminnow, razorback sucker, and humpback chub and the physical processes that affect their habitats because information was available to recommend specific flow and temperature regimes to benefit extant populations of each species. Similar information was not available for bonytail, but the flow and temperature recommendations that are made for the other endangered fishes would presumably benefit any bonytails that may remain in the system and would not limit their future recovery potential.

The report summarizes the scientific information currently available on the effects of Flaming Gorge Dam on the endangered fishes. This information will be used to develop a new biological opinion on operation of the dam and may also serve as a basis for evaluating potential impacts and mitigation measures for other ongoing or future projects that could affect flow, temperature, and sediment regimes in the Green River. Information is presented on river hydrology, geomorphology, and the biology of the endangered fishes (including distribution and abundance, flow-habitat requirements, reproduction, recruitment, diet, population dynamics, and interspecific interactions) in the Green River system.

Other important resources and concerns could be directly or indirectly affected by implementation of the flow and temperature recommendations for the endangered fishes. These include other threatened or endangered species (e.g., bald eagle *Haliaeetus leucocephalus* and Ute ladies'-tresses *Spiranthes diluvialis*), other native and nonnative fishes, riparian wildlife, flooding of private and public properties, nuisance weeds and pests (e.g., mosquitos), power generation, water supply, and recreation. However, assessment of the overall effects of implementing the recommendations is deferred to other regulatory or public-involvement processes. Reclamation intends to prepare an environmental impact statement (EIS) on implementation of the flow and temperature recommendations included in this report. This EIS would examine impacts of the proposed action (implementation of the recommendations) on other resources.

1.2 CHANGES IN RIVER ECOSYSTEMS OF THE COLORADO RIVER BASIN

The riverine ecosystem of the Colorado River basin (Figure 1.1) has been greatly altered over the past 100 years by human activities. Throughout the basin, major changes in the physical and biological characteristics of rivers have resulted from the cumulative effects of (1) construction and operation of dams for water supply and hydroelectric generation, (2) channelization and diking of main-stem areas and tributary streams, (3) water withdrawals for irrigation and municipal use, (4) introduction and proliferation of nonnative fishes, and (5) pollution.

The construction and operation of dams have had profound effects on riverine ecology in the basin. Large areas of riverine habitat upstream of the dams have been eliminated by inundation and replaced by lentic habitat. Through time, aquatic communities have developed in reservoirs;

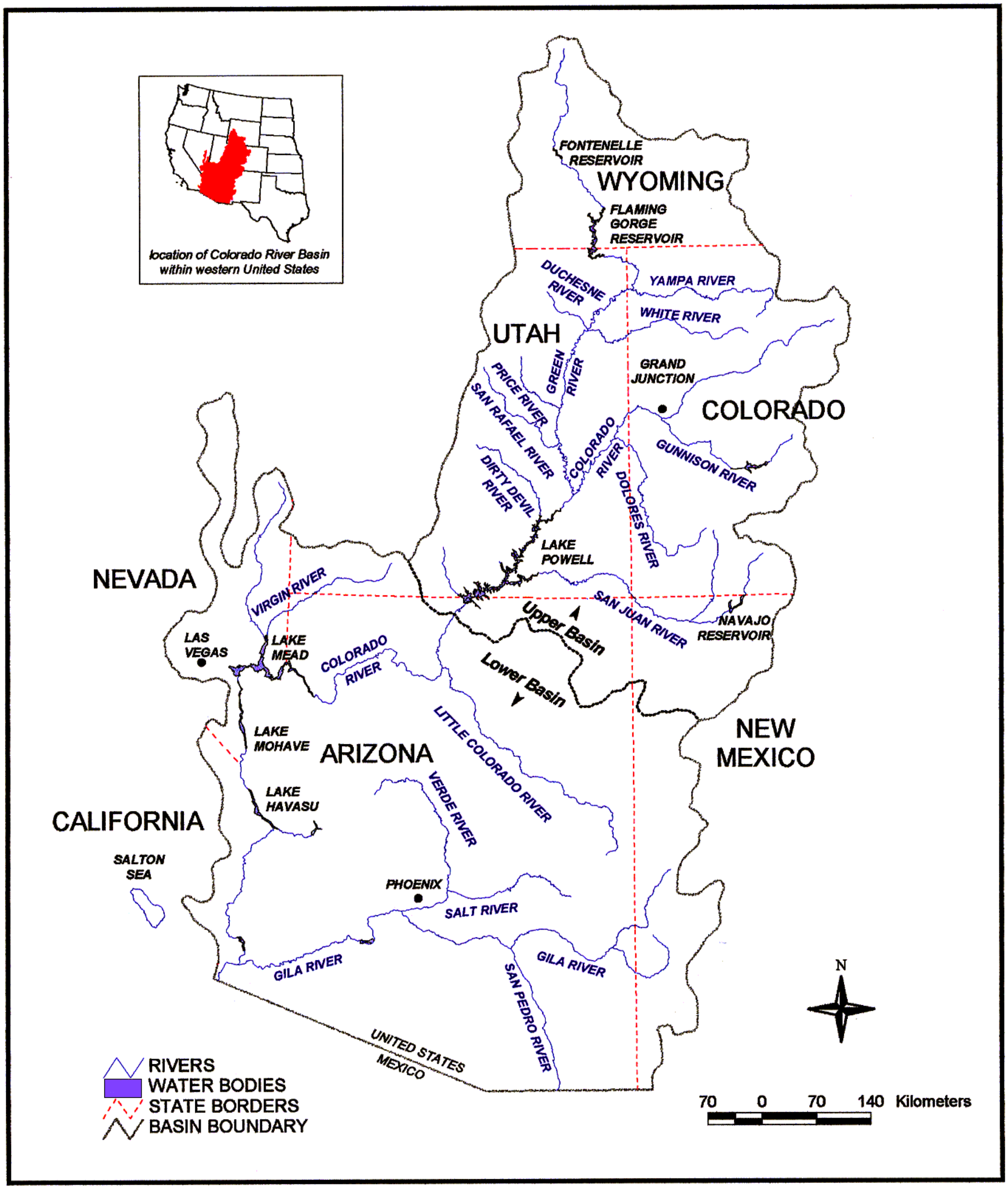

Figure 1.1.—Colorado River basin.

these aquatic communities are quite different from those that existed prior to dam construction. They developed naturally as a result of altered physical conditions or artificially as a result of active management of reservoir fisheries, particularly stocking of nonnative fishes. Dams also have reduced or eliminated movement of native fishes between river sections and thus resulted in population fragmentation.

Riverine habitat does persist downstream of dams, but flow patterns, sediment loads, and water temperatures in rivers are altered by water-release patterns dictated by power demands, irrigation needs, flood control, and recreational uses. These changes have had dramatic effects on downstream physical conditions, and native aquatic organisms that are adapted to the natural dynamic flow, sediment, and temperature regimes typically decline after dam closure. Sediment loads in rivers immediately downstream of dams are reduced because sediment carried by rivers drops out of suspension in the slack water of reservoirs. Water released from dams typically has very little sediment load and consequently erodes any existing sediment deposits in dam tailwaters. This process, called "armoring," eventually produces areas where the river bed becomes eroded to cobbles, boulders, or bedrock, with very little, if any, fine sediment deposits.

> ***Tailwater*** – The portion of a river downstream of a reservoir that exhibits water conditions (such as temperature and clarity) that are very similar to the conditions of the water being withdrawn from the reservoir. Releases from the hypolimnion of a reservoir often provide clear, cold water in the tailwater that can support cold-water sport fisheries. The tailwater for Flaming Gorge Dam extends about 26 km downstream of the dam.
>
> ***Hypolimnion*** – The lowermost layer of water in a thermally stratified lake that is denser and colder than water in strata higher in the water column. The density differences between the hypolimnion and upper water layers reduces mixing between the layers.

Changes in riverine thermal characteristics may be one of the greatest physical alterations precipitated by dam construction and operation (Ward and Stanford 1979; Petts 1984; Stanford and Ward 1986a; Stanford et al. 1996). The temperature of water released from dams tends to be colder in summer and warmer in winter than the temperature of unregulated rivers because releases generally draw from the hypolimnion of reservoirs. These changes in water temperature can affect river productivity and the distribution, behavior, growth, and survival of fishes. The net effect is to reset the species composition of a tailwater assemblage to one similar to that found in cold, higher-elevation upstream reaches. Native fishes formerly present in the area reappear in downstream river sections only after temperatures recover from natural warming or because of tributary amelioration. As a consequence, tailwater habitat downstream of hypolimnetic-release dams often supports nonnative fishes adapted to cold-water conditions (e.g., trout) where native warm-water biota once existed (Holden 1979; Stanford and Ward 1986b; Carlson and Muth 1989; Stanford et al. 1996). Resource managers have exploited this change in water temperature to develop cold-water trout fisheries in tailwaters of most dams in the basin.

Water depletion and river regulation can not only reduce annual flow volumes but can also change seasonal and daily flow patterns, which can also be important. River flows downstream of a hydroelectric dam generally exhibit much less seasonal variation but more daily variation than flows in an unregulated river. Seasonal variation decreases as a result of water storage and intentional limitation of releases to accommodate power-generation capacities. Daily variation increases as hydroelectric generation fluctuates in response to daily demands for electricity. Changes in natural seasonal and daily flow patterns affect riverine ecology in a number of ways. Lower spring flows are less effective than higher flows in transporting sediment, forming and rehabilitating important in-channel habitats, scouring encroaching riparian vegetation, and maintaining habitat complexity. In unregulated rivers, overbank flooding in spring during wetter years inundates floodplain wetlands that supply nutrients and organic material to the main channel and serve as important growth and conditioning habitats for some native fishes. Connections between these warm, productive habitats and the river are eliminated or reduced at lower spring discharges resulting from typical dam operations. Higher summer flows limit the formation of backwaters, used as primary nursery areas by many native fishes, and they reduce water temperatures. Higher winter flows flood low-velocity habitats and can potentially displace and stress fish. Daily fluctuations in flow may affect the stability and productivity of nearshore quiet-water habitats (e.g., backwaters).

Effects of regulation on river flow, sediment load, and temperature diminish at increasing distances downstream of dams. Daily flow fluctuations are naturally attenuated by longitudinal changes in channel morphology, and river water warms naturally as it is exposed to sunlight and heated land surfaces along the channel margin. Tributary inputs also ameliorate effects of dams on flow, sediment, and temperature. Tributaries can contribute significant quantities of sediment to the main channel and replenish sediment deposits, particularly during peak-flow events. Tributaries also can restore a more natural seasonal pattern of flow, reduce daily fluctuations produced by hydropower operations, and increase water temperatures. The relative influence of tributaries depends on the size of their drainages, their sediment-load characteristics, and the degree of river regulation.

The natural ecology of rivers also has been affected by widespread increases in nonnative fishes that were intentionally (to create or support sport fisheries) or accidentally introduced into the basin. Reductions in the distribution and abundance of native fishes in the Colorado River basin have been attributed partially to the establishment of more than 60 nonnative fishes (Carlson and Muth 1989). Introduced species vary in body size, environmental tolerances, and habitat preferences and are widely distributed and abundant. For example, more than 95% of small-bodied fishes found in Green River backwaters occupied by native fishes in early life stages are nonnative cyprinids (Haines and Tyus 1990; McAda et al. 1994a; Bestgen and Crist 1999; Day et al. 1999a, 1999b; Trammell and Chart 1999). Because of their wide distribution, high abundance, and diets ranging from herbivory to piscivory (Tyus and Karp 1989; Tyus and Karp 1991; Muth and Snyder 1995), introduced fishes are potential competitors with or predators of native fishes in nearly all life stages. Although both cold-water (e.g., rainbow trout *Oncorhynchus mykiss* and brown trout *Salmo trutta*) and warm-water species (e.g., red shiner *Cyprinella lutrensis*, common carp *Cyprinus carpio*, channel catfish *Ictalurus punctatus*, green sunfish *Lepomis cyanellus*, and smallmouth bass *Micropterus dolomieui*) can adversely affect native fishes (Hawkins and Nesler 1991; Lentsch et al. 1996b; Tyus and Saunders 1996), warm-water species have the greatest potential impact because their habitat preferences are similar to those of most native species.

As a result of these and other ecological changes, many of the native fishes of the Colorado River system are in jeopardy and protected under the 1973 Endangered Species Act, as amended, or by one or more of the basin states (Carlson and Muth 1989, 1993). All of the “big-river” fishes endemic to the Colorado River basin are in jeopardy (Minckley 1973; Tyus et al. 1982a; Behnke and Benson 1983; Williams et al. 1985; Minckley et al. 1991a; Tyus 1991a), including the federally endangered humpback chub (USFWS 1967), bonytail (USFWS 1980), Colorado pikeminnow (USFWS 1974), and razorback sucker (USFWS 1991b). Remaining populations of humpback chub occur in the Grand Canyon in the lower Colorado River basin and in five canyon regions in the upper basin (Valdez and Ryel 1995, 1997). The bonytail, originally widespread and abundant, is now considered functionally extinct in the wild (USFWS 1990b). Wild Colorado pikeminnow are extirpated from the lower basin (Tyus 1991a), and the razorback sucker exists naturally as only a few disjunct populations or as scattered individuals (Minckley et al. 1991a).

1.2.1 The Green River System

Completion of Flaming Gorge Dam on the Green River in 1962 had profound effects on downstream conditions. Before construction of the dam, the Green River was an unregulated, turbid, temperate stream that exhibited seasonal variations in flow and temperature on the basis of natural flow cycles. The natural flow pattern (Section 3.4.1) featured a high spring peak flow and low base flows with periodic spates caused by localized rainfall. Water temperatures in the river ranged from near freezing in winter to greater than 20ºC in summer (Vanicek et al. 1970). A diverse assemblage of warm-water species dominated the aquatic macroinvertebrate fauna (Holden and Crist 1981), and vegetation along the river occupied two distinct zones (Fischer et al. 1983). Plants in the flood zone nearest the river were predominantly annual or scour-tolerant perennials such as wild licorice *Glycyrrhiza lepidota*, dogbane *Apocynum* spp., and sedges *Carex* spp. Dominant plants above the flood zone included box elder *Acer negundo*, squawbush *Rhus trilobata*, Fremont cottonwood *Populus fremontii*, and coyote willow *Salix exigua* (Holmgren 1962). The fish community of the main-stem river consisted of 12 native species (Table 4.1), represented primarily by warm-water cyprinids (minnows) and catostomids (suckers), as well as at least six species of introduced nonnative fishes (Table 4.2; Vanicek et al. 1970).

The presence and historic operation of Flaming Gorge Dam greatly altered seasonal and daily flow (Section 3.4) and temperature patterns (Section 3.5) in the Green River. The magnitude and duration of spring peak flows were reduced, the magnitude of base flows was increased, daily fluctuations in flow were increased, and hypolimnetic releases of water from the reservoir affected water temperatures and increased water clarity. These changes rendered sections of the Green River directly downstream of the dam largely unsuitable for many native fishes (Chapter 4); shifted the local aquatic macroinvertebrate community to species tolerant of clear, cold water (Vinson 1998); and allowed the establishment of a tailwater trout fishery (Modde et al. 1991). When the large annual floods were eliminated, riparian vegetation from adjacent riparian and upland areas colonized much of the old flood zone and in-channel sand or gravel bars; it formed dense stands along shorelines in some areas and, by stabilizing sediment deposits, gradually made the channel narrower and deeper, with steep banks.

The Yampa River is the largest remaining essentially unregulated river in the upper Colorado River basin, and its inflow into the Green River, 105 km downstream of Flaming Gorge Dam, ameliorates some effects of dam operation on river flow, sediment load, and temperature. As a result, endangered fishes in the Green River are now primarily restricted to sections downstream of the Yampa River confluence (Figure 1.1), where they occupy habitats also used by 21 nonnative fish species (Table 4.2). Holden (1980) concluded that flows from the Yampa River, especially spring peak flows, were crucial to the maintenance of the Green River's "large-river" characteristics and, therefore, very important to maintaining suitable conditions in the Green River downstream of the confluence. He speculated that loss of natural flows from tributaries of the Green River, especially the Yampa River, could push the endangered fish species closer to extinction and recommended against regulation of Yampa River flows (Holden 1980).

In 1990, the Service developed interim flow recommendations for the Yampa River (USFWS 1990c) that were based on a review of existing biological data on endangered fishes in the Green and Yampa rivers (Tyus and Karp 1989). Those interim recommendations called for preservation of a natural seasonal pattern of flows in the Yampa River, including spring peak flows that reflected the natural hydrologic regime and base flows equal to the 50% flow-exceedance level[2] as measured at the U.S. Geological Survey (USGS) gage near Deerlodge Park. The recommended interim flows followed a "stair-stepped" pattern that reflected the use of mean monthly flows for a given period. Harvey et al. (1993) identified the importance of the high spring peak flows in the Yampa River for creating and maintaining conditions to promote spawning by Colorado pikeminnow on cobble and gravel bars. Modde and Smith (1995) reexamined the interim recommendations in light of additional studies conducted on endangered fishes in the Green and Yampa Rivers in order to develop revised flow recommendations. They identified a need to maintain natural variability by allowing flows to be driven by natural daily variability instead of average monthly flows. Additional recommendations for August–October base flows needed by subadult and adult Colorado pikeminnow in the Yampa River were made by Modde et al. (1999), in which a minimum target base flow of about 3 m^3/s was identified.

Flows in other tributaries, especially the Duchesne, White, Price, and San Rafael Rivers, also are important to the maintenance of conditions in the Green River. The Service developed preliminary flow recommendations for the Duchesne River (USFWS 1998b) that identified flows for all months of the year under wet (25% exceedance), average (50% exceedance), and dry (75% exceedance) hydrologic conditions. Additional research is underway to refine flow recommendations for the Duchesne River. The Service currently is in the process of developing flow recommendations for the White River, and it is anticipated that flow recommendations for other Green River tributaries also will be developed in the future.

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[2]Exceedance values refer to the percentage of recorded flows that are higher than that value. An exceedance value is equivalent to 1 minus the percentile.

1.3 1992 BIOLOGICAL OPINION ON OPERATION OF FLAMING GORGE DAM

In 1980, Reclamation entered into Section 7 consultation with the Service on operation of Flaming Gorge Dam. Studies on the biology and hydrology of the Green River conducted during 1978–1989 (Table 1.1) culminated in preparation of the Biological Opinion (USFWS 1992), which concluded that historic operations of Flaming Gorge Dam (i.e., dam operations prior to 1992) jeopardized the continued existence of endangered fishes in the Green River. The reasonable and prudent alternative of the Biological Opinion included the following five elements.

1. *Refinement of the operation of Flaming Gorge Dam so that flow and temperature regimes of the Green River will more closely resemble historic conditions*. Under this element, seasonal flow and summer temperature recommendations were established to enhance the status of endangered and other native fishes in the Green River system downstream of Flaming Gorge Dam. Recommendations for spring, summer/autumn, and winter periods were based on information presented in consolidated biology (Tyus and Karp 1991) and hydrology (Smith and Green 1991) reports. However, recommendations for each season were supported by differing levels of biological and physical data, with the most comprehensive data set covering summer through autumn.

2. *Conduct a 5-year research program, including implementation of winter and spring research flows beginning in 1992, to allow for potential refinement of flows for these seasons*. Except for specific winter and spring research flows during the research program, Green River flows were to resemble the historic natural hydrograph to the extent possible. This element was included so that biological and physical responses of the Green River ecosystem to the recommended flows and temperatures could be evaluated. Additionally, because winter and spring flow recommendations were based on limited information, more research was needed to refine flow recommendations for those seasons.

3. *Determine the feasibility and effects of releasing warmer water during the late spring/summer period and investigate the feasibility of retrofitting river bypass tubes to include power generation, thereby facilitating higher spring releases*. A multilevel intake structure was installed at Flaming Gorge Dam in 1978 that allowed selective release of warmer water during most seasons of the year. However, water temperatures in the Green River between Flaming Gorge Dam and the confluence with the Yampa River in Echo Park often remain below those deemed suitable for reproduction and growth of the endangered fish species from spring through autumn. Consequently, this element required examination of the feasibility of further narrowing the temperature differential between warmer water entering the Green River from the Yampa River and cooler water in the Green River upstream of the confluence with the Yampa River during the spring and summer.

Table 1.1.—Studies conducted in support of the 1992 Biological Opinion on Operation of Flaming Gorge Dam.

BIOLOGICAL STUDIES

Study 1—Summer and Autumn Requirements of Age-0 Colorado Squawfish in the Green River

- Distribution, Habitat Use, and Growth of Young Colorado Squawfish in the Green River Basin (Tyus and Haines 1991)
- Movements and Habitat Use of Young Colorado Squawfish in the Green River (Tyus 1991b)

Study 2—Winter Habitat and Flows for Adult and Young Colorado Squawfish and Adult Razorback Sucker

- Winter Habitat Study of Endangered Fish — Green River: Wintertime Movement and Habitat of Adult Colorado Squawfish and Razorback Suckers (Valdez and Masslich 1989)
- Winter Habitat Use of Young Colorado Squawfish (Tyus 1991b)

Study 3—Spring–Early Summer Flow Requirements of Colorado Squawfish, Razorback Sucker, and Humpback Chub

- Potamodromy and Reproduction of Colorado Squawfish in the Green River Basin, Colorado and Utah (Tyus 1990)
- Responses of Young Razorback Sucker and Colorado Squawfish to Water Flow and Light Intensity (Paulin et al. 1989)
- Population Size and Status of Razorback Sucker in the Green River Basin, Utah and Colorado (Lanigan and Tyus 1989)
- Spawning and Movements of Razorback Sucker, *Xyrauchen texanus*, in the Green River Basin of Colorado and Utah (Tyus and Karp 1990)
- Humpback Chub (*Gila cypha*) in the Yampa and Green Rivers, Dinosaur National Monument, with Observations on Roundtail Chub (*Gila robusta*) and other Sympatric Species (Karp and Tyus 1990b)
- Age determination in Colorado Squawfish and Razorback Sucker (Minckley et al. 1991b)

Study 4—Fish Community Interactions of Endangered and Introduced Fishes

- Fish Associations and Environmental Variables in Age-0 Colorado Squawfish Habitats, Green River, Utah (Haines and Tyus 1990)
- Behavioral Interactions between Young Colorado Squawfish and Six Fish Species (Karp and Tyus 1990a)
- *Esox lucius* (Esocidae) and *Stizostedion vitreum* (Percidae) in the Green River Basin, Colorado and Utah (Tyus and Beard 1990)
- Growth, Diet, and Status of Channel Catfish, *Ictalurus punctatus*, in the Green and Yampa Rivers, Colorado and Utah (Tyus and Nikirk 1990)
- Migrating Mormon Crickets, *Anabrus simplex* (Orthoptera: Tettigoniidae), as Food for Stream Fishes (Tyus and Minckley 1988)

Table 1.1.—Continued.

Study 5—Trophic Dynamics and Ecological Interactions in Important Backwater Habitats
• Some Aspects of Trophic Interactions in Selected Backwaters and the Main Channel of the Green River, Utah, 1987–1988 (Grabowski and Hiebert 1989)
Study 6—Mapping of Important Backwater Habitats of Colorado Squawfish
• Comprehensive Report (1986–1988) on the Effects of Green River Flows on Backwater Habitat Availability as Determined by Remote Sensing Techniques (Pucherelli and Clark 1989)
HYDROLOGICAL MODELING STUDIES
Study 1—HYDROSS Monthly Flow Model
Study 2—Peaking Power Model
Study 3—Channel Stability Model
Study 4—Temperature Model

The bypass tubes at Flaming Gorge Dam are capable of releasing approximately 113 m^3/s of water in addition to the water releases of 130 m^3/s that can be accommodated through the power plant. One concern over utilizing bypass flows to increase the magnitude of the spring peak releases from Flaming Gorge Dam is that no electric power is generated by this water. Consequently, the Biological Opinion called for examination of the feasibility of retrofitting the bypass tubes to include power generation capability.

4. *Legal protection of Green River flows from Flaming Gorge Dam to Lake Powell*. The state of Utah has indicated that until quantifiable recommendations are made for flows throughout the Green River (i.e., from Flaming Gorge Dam to Lake Powell), legal protection of flows will not be pursued. The Biological Opinion only recommends target flows in the Green River near Jensen, Utah. Therefore, the Flaming Gorge Flow Recommendations Investigation contained provisions for collecting data to identify and recommend flows and temperatures required to enhance and recover endangered fishes of the Green River ecosystem from Flaming Gorge Dam to the confluence with the Colorado River.

5. *Initiate discussions with the Service after conclusion of the 5-year research program to examine further refinement of flows for the endangered Colorado River fish.* Under this element, results of the research program will be used to reevaluate and, if necessary, refine recommendations presented in the 1992 Biological Opinion.

Flow recommendations in the 1992 Biological Opinion for spring, summer, autumn, and winter (element 1 of the reasonable and prudent alternative) were based on the best available information and professional judgment of researchers who had collected and analyzed much of the data. The recommended flows were intended to restore the natural hydrograph to the extent possible and to provide a flow regime that would allow for enhancement and recovery of endangered and other native fishes in the Green River from the confluence of the Green and Yampa Rivers to Lake Powell. Because of data limitations and the location of areas believed to be crucial for protection of the endangered fishes, the Biological Opinion only recommended seasonal target flows for the Green River at the USGS gage near Jensen, Utah (located 157 km downstream from the dam). The seasonal flow and summer temperature recommendations are summarized below; the Biological Opinion provides additional details.

> ***Power-plant capacity releases*** – Reservoir releases through the power plant that generate electricity. Power-plant releases from Flaming Gorge Dam typically range from 23 to 130 m^3/s.
>
> ***Bypass tubes*** – Flaming Gorge Dam has two steel-lined tubes with a combined capability of releasing up to 113 m^3/s of water. Water released through the bypass tubes does not produce electric power.
>
> ***Spillway*** – A gated overflow structure that can release up to 793 m^3/s of water through a spillway tunnel. Water released through the spillway does not produce electric power.
>
> ***Penstocks*** – 3-m diameter tubes that carry water from the reservoir to the turbines at the base of the dam. A selective withdrawal structure was added to Flaming Gorge Dam's penstocks in 1978 so that water could be withdrawn from selected depths in the reservoir, thereby allowing some control over the temperature of the water released from the dam.

- ***Spring.***—Timing and duration of spring releases from Flaming Gorge Dam are to be patterned after the spring flows of the Yampa River. Water releases from Flaming Gorge Dam are to begin increasing at a rate of no more than about 11.3 m^3/s per day between 1 April and 15 May until a peak release of approximately 113–133 m^3/s is attained. Peak releases are to be maintained for 1–6 weeks beginning between 15 May and 1 June, and the timings of these releases are to coincide with peak spring runoff in the Yampa River so that a target peak flow of 368–509 m^3/s is attained at the USGS gage near Jensen, Utah. The duration of peak releases is to depend on the hydrological and meteorological conditions for a given year, with a longer release period to be used during high water years. The descending arm of the hydrograph is to be synchronized with the conclusion of spring runoff conditions in the Yampa River, and changes in releases from Flaming Gorge Dam are to be limited to no more than 11.3 m^3/s per day during this period. During average water years, the entire spring peak is to occur over 6 to 8 weeks. If it becomes necessary to bypass water from the dam to alleviate storage problems, then the bypass should occur during or before the Yampa River spring peak.

- ***Summer.***—Water releases from Flaming Gorge Dam should decrease following the spring peak until a flow of 31–51 m^3/s is attained at the Jensen gage (actual flow within the recommended range is to be based on hydrologic conditions and Reclamation needs). Fluctuations in flow at the Jensen gage are to be limited to no more than 25%

(based on hourly values) around the flow established for a given summer period, and flows are not to be outside the 31–51 m^3/s range. The date for achieving the target flow is to be based primarily on the anticipated hydrograph of the Yampa River. During normal or high water years, the target flow is expected to be achieved on or near 10 July or 20 July, respectively. During low water years, the target flow is expected to be achieved on or near June 20. Water released from Flaming Gorge Dam through the multilevel-intake structure between 1 July and 1 November should be the warmest water available (approaching 15ºC). By releasing the warmest water available during this period, water temperatures in the upper Green River should not differ more than 5ºC from the temperature in the Yampa River at Echo Park and should average near 22–25ºC in Gray Canyon from 1 July to 15 August.

- ***Autumn*.**—Autumn flows are to be a continuation of the summer flows described above. During high water years, however, the upper limit of the target-flow range could be increased up to a maximum of 68 m^3/s, because most young-of-year (YOY) endangered fishes are expected to be past the larval period of development by autumn. If water conditions change substantially, a new target flow can be selected on or after 15 September. Fluctuations in flow at the Jensen gage in autumn are to be limited to no more than 25% (based on hourly values) around the autumn target and are to be maintained within the bounds of the 31–68 m^3/s range until 1 November of each year.

- ***Winter*.**—Winter flows should be stabilized once ice cover has formed and should remain stable until ice breakup. An exception to this recommendation is to be allowed when evidence shows that higher winter flows are needed to achieve low summer and autumn flows. If ice formation does not occur or if specific research flows are not requested, water releases from Flaming Gorge Dam are to be based on agreements between Reclamation and the State of Utah or the need to release more water during high water years. If possible, flow fluctuations are to be moderated during winter.

The 1992 Biological Opinion also called for additional research over 5 years to collect information needed to refine the flow and temperature recommendations (particularly flow recommendations for spring and winter) and to develop flow recommendations for other areas of the Green River (element 2 of the reasonable and prudent alternative). To address this need, the Recovery Program initiated the Flaming Gorge Flow Recommendations Investigation (Chapter 2) in 1992 to evaluate biological and physical responses of the Green River ecosystem to the seasonal flow recommendations in the Biological Opinion and to obtain information that could be used to refine the existing flow recommendations for the Green River on the basis of test-flow releases from Flaming Gorge Dam. Data collection for the Flaming Gorge Flow Recommendations Investigation concluded in 1996. During 1990 and 1991, while the Biological Opinion was being developed, research was conducted to further assess reproduction and nursery habitats of Colorado pikeminnow; those studies are considered part of the Flaming Gorge Flow Recommendations Investigation.

2 FLAMING GORGE FLOW RECOMMENDATIONS INVESTIGATION

This chapter presents an overview of the Flaming Gorge Flow Recommendations Investigation, which serves as the basis of this report. It discusses the origins of the investigation, study area, study objectives and approach, research flows implemented during the study period, and methods used to develop the integrated flow and temperature recommendations presented in Chapter 5.

In 1990, the USFWS and Reclamation submitted a proposal to the Recovery Program that called for a cooperative agency approach to conduct additional research on the effects of operating Flaming Gorge Dam on endangered fishes in the Green River system. As a result, a team composed of upper-basin researchers was assembled to design and conduct studies that would provide data for refinement of flow and temperature recommendations in the 1992 Biological Opinion (USFWS 1992; Section 1.3). The Flaming Gorge Research Team consisted of representatives from the Service, Reclamation, Colorado State University Larval Fish Laboratory, Utah Division of Wildlife Resources, Argonne National Laboratory, Utah State University, National Park Service, and BIO/WEST, Inc. The Service and Reclamation were responsible for coordinating annual research efforts. Studies for the Flaming Gorge Flow Recommendations Investigation were conducted from 1990 through 1996, but flow and temperature recommendations specified in the Biological Opinion were not fully implemented until 1992.

2.1 STUDY AREA

The study area for the Flaming Gorge Flow Recommendations Investigation encompassed the main-stem Green River from Flaming Gorge Dam downstream to its confluence with the Colorado River and included lower portions of major tributaries (Figure 2.1). Areas of particular interest, based on past research, included the lower Yampa River; the Green River between the Yampa River confluence and Jensen, Utah; the Green River between Jensen and Ouray, Utah; the Green River through Desolation and Gray Canyons; and the Green River upstream of the town of Green River, Utah. In this report, the main-stem Green River is divided into the following contiguous reaches delimited by major tributaries for evaluation and development of flow and temperature recommendations: (1) Flaming Gorge Dam to the Yampa River confluence, (2) Yampa River confluence to the White River confluence, and (3) White River confluence to the Colorado River confluence (Figure 2.1). These reaches are described in Section 3.3.

2.2 STUDY OBJECTIVES AND APPROACH

The Flaming Gorge Flow Recommendations Investigation was designed to (1) determine the biological and physical responses to seasonal flow modifications of the Green River ecosystem from Flaming Gorge Dam to the Green River confluence with the Colorado River, (2) develop

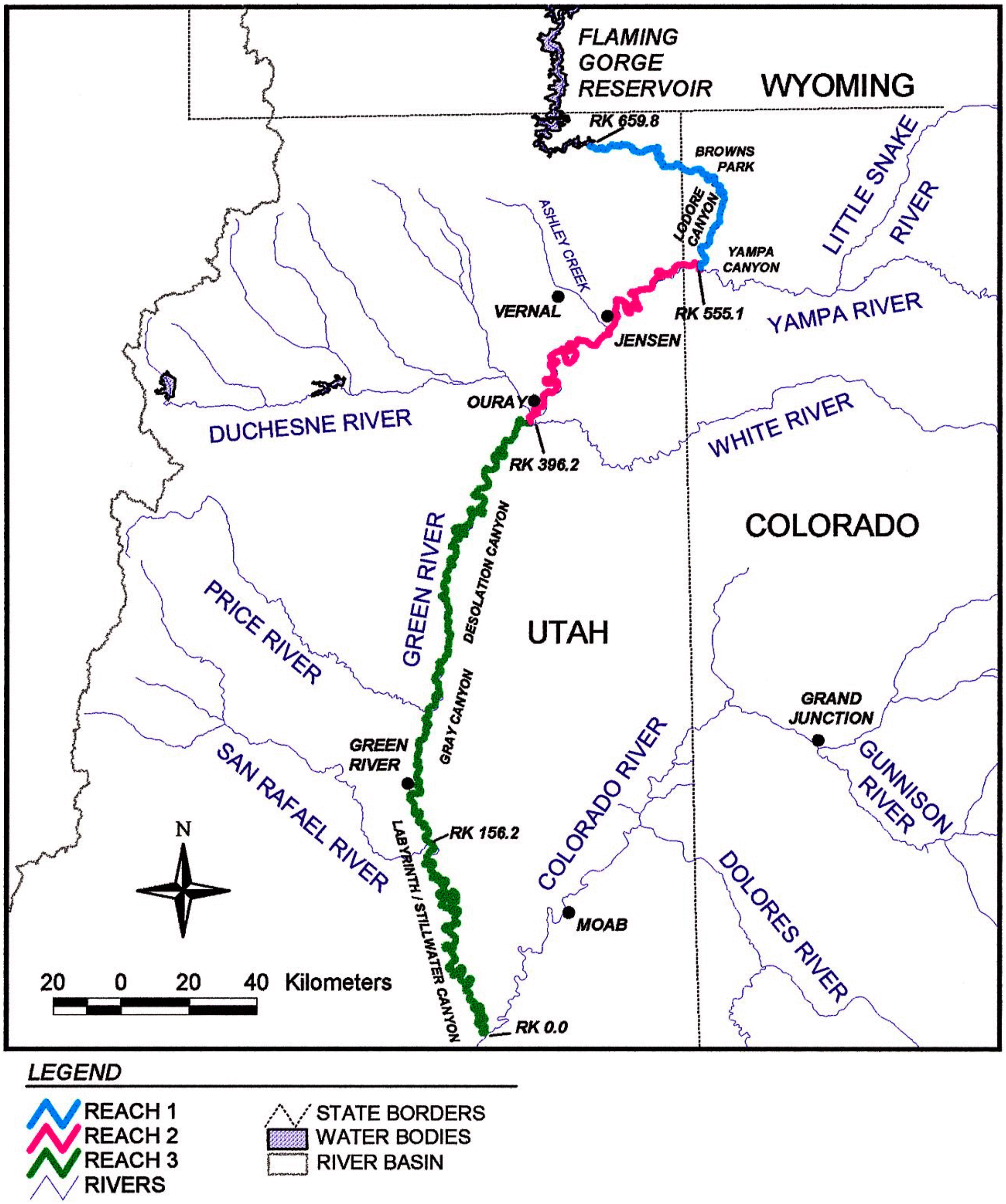


Figure 2.1.—The Green River study area.

reliable data for refining the flow recommendations in the 1992 Biological Opinion, and (3) investigate potential effects of increasing the temperature of water released from Flaming Gorge Dam. The four major objectives of the investigation were to:

1. Track reproduction of the endangered fishes in the Green and lower Yampa Rivers and determine relationships among seasonal flows, water temperatures, and reproductive success;

2. Evaluate recruitment of the endangered fishes from age 0 to subsequent life-history stages and determine relationships among seasonal flows, water temperatures, and survival of young fish;

3. Monitor the relative abundance and population structure of the endangered fishes in order to acquire information on interactions among fish species and how flows may differentially affect populations; and

4. Determine how releases from Flaming Gorge Dam and flows from tributaries affect the formation and maintenance of important habitats for the endangered fishes throughout the Green River.

When designing the Flaming Gorge Flow Recommendations Investigation, the following considerations were deemed important by the research team:

- The research program should address all endangered fishes to the extent possible. Nonnative and other native fishes should also be considered, especially in terms of their interactions with endangered fishes. Endangered fishes included humpback chub, Colorado pikeminnow, and razorback sucker.

- Long-term, standardized studies extending for the length of the research period would be needed to provide a database for assessment of the biological and physical responses of the Green River ecosystem to implemented flow recommendations.

- The framework of the long-term effort should be sufficiently simple and flexible to allow for continuity over time and collection of accurate quantitative data covering important life-history stages. Consideration was given to the ability to link new data with existing data and information generated from the Interagency Standardized Monitoring Program (ISMP) and other studies. Research within the Flaming Gorge Flow Recommendations Investigation should be coordinated with other studies or programs in the Recovery Program such as ISMP, channel monitoring, and hydrology support and with other research activities in the Green River funded outside of the Recovery Program.

- Because the state of knowledge about the biology and life history of the Colorado pikeminnow was more complete than knowledge about the humpback chub and razorback sucker, the flow regime specified in the Biological Opinion emphasized Colorado pikeminnow needs. Long-term studies would initially focus on Colorado pikeminnow, and shorter-term studies would be planned for the other endangered fishes. As knowledge about the biology and life history of the other endangered fishes increased, the long-term effort would be modified and expanded to include these species.

- Establishing links among reproduction, recruitment of young fish, recruitment to adult stocks, status of populations, and hydrologic conditions would be critical.

- Two important Colorado pikeminnow spawning areas had been identified in the Green River system (i.e., lower Yampa Canyon and Desolation/Gray Canyons). Representative sampling in river sections downstream of each of these spawning areas would be needed to provide an accurate assessment of annual reproduction and recruitment of young.

- Sampling of adult Colorado pikeminnow immediately before and during spawning should be minimized to reduce disturbance and sampling mortality. Sampling of all endangered fishes should be coordinated to eliminate unnecessary duplication of effort and to minimize impacts on fish, particularly at spawning locations.

- Collection of life-history, abundance, and other data on all fishes would be important.

Therefore, the overall Flaming Gorge Flow Recommendations Investigation consisted of three interrelated efforts that differed in scope and duration. Long-term studies were conducted to track changes in populations and habitats across years. Shorter, more focused studies examined specific questions that arose during long-term studies or addressed specific flow relationships. Other studies evaluated the efficacy of specific experimental projects, particularly in the Ouray area, to potentially improve habitat conditions for the endangered fishes; the Recovery Program's Habitat Restoration Program eventually assumed responsibility for these studies and projects. The Flaming Gorge Flow Recommendations Investigation also considered and incorporated results of other relevant contemporary investigations funded by the Recovery Program, National Park Service, Reclamation, or Central Utah Water District. Studies conducted under the Flaming Gorge Flow Recommendations Investigation are presented in Table 2.1. Abstracts of these studies and of selected studies from other investigations are presented in Appendix B.

2.3 RESEARCH FLOWS

The 1992 Biological Opinion recommended implementation of a specific set of research flows. During this investigation, research flows were implemented primarily in spring and winter

Table 2.1.—Studies included in the Flaming Gorge Flow Recommendations Investigation.

Movement and Habitat Use of Channel Catfish and Common Carp in the Upper Green River and Yampa River. (Project #5d)
Temperature Effects on Survival of Razorback Sucker, Flannelmouth Sucker, and Bluehead Sucker Embryos and Survival and Growth of Fry. (Project #5e)
Early Biology Studies—Investigations of Effects of Flow, Temperature, and Other Environmental Variables on the Early Biology of Selected Fishes in the Green River System. (Project #12-9)
An Evaluation of Fish Predation on Invertebrates in Backwater Habitats in the Green River. (Project #12-10)
An Evaluation of Mark and Recapture Methods for Use in Determining Colorado Squawfish Recruitment. (Project #18-4)
Nonnative Fish Management. (Project #18-8)
Synthesis of Winter Movement and Habitat of Adult Colorado Squawfish and Razorback Sucker in the Green River below Flaming Gorge Dam. (Project #18-11)
Analysis of Past Collections for Young Humpback Chub and Razorback Sucker. (Project #15)
Annual Assessment of Colorado Squawfish Reproduction and Larval Abundance in the Lower Yampa River, Colorado, and Green River, Utah. (Project #32)
Assessment of Colorado Squawfish Nursery Habitat in the Green River. (Project #33)
Annual Assessment of Spawning Success, Larval Distribution, and Habitat Selection of Mainstem Razorback Sucker. (Project #34)
Flow Effects on Overwinter Survival of YOY Colorado Squawfish in the Green River. (Project #35)
Growth of Young Colorado Squawfish as Related to Adult Recruitment. (Project #35)
Effects of Winter and Spring Flows on Movements, Dispersal, and Survival of Young Colorado Squawfish. (Project #36)
Quantification of the Role of Flaming Gorge Dam, in Relation to Other Driving Mechanisms, in Causing Changes in Aquatic Habitat Availability in the Green River. (Project #37)
Investigations Into Potential Razorback Sucker and Colorado Squawfish Spawning in the Lower Green River. (Project #38)
Reproduction and Recruitment of *Gila* Sp. and Colorado Squawfish in the Middle Green River. (Project #39)
Evaluation of Restoration Potential of the Green River Upstream of the Yampa River. (Project #40)
Effects of Flow Regulation and Ice Off on Overwinter Nursery Habitat of Age-0 Colorado Squawfish in the Green River below Flaming Gorge Dam. (Project #41)
Availability of Habitat Characteristics and Use of Spring Habitats for Colorado Squawfish and Razorback Sucker in the Green River. (Project #49)

because there was less information on fish flow needs in these seasons. Requests or recommendations for research flows were submitted to Reclamation and discussed at biannual meetings of the Flaming Gorge Operations Work Group, which included members from the Service, Reclamation, State of Utah, Western Area Power Administration (Western), other affected agencies, and the public.

Flow requests made by the Flaming Gorge Research Team varied depending on study needs and available water resources. The Biological Opinion required that research flows would include at least 1 year with stable winter releases at or less than 57 m^3/s from Flaming Gorge Dam and at least 1 year that featured a spring peak release of approximately 510 m^3/s measured at the Jensen gage (using bypass tubes at Flaming Gorge Dam if needed). The Biological Opinion also required the research program to examine spring peak flows of different magnitudes and durations. In addition to the flows required in the Biological Opinion, the Flaming Gorge Research Team requested stable releases from Flaming Gorge Dam to support studies for short periods of time during summer through winter in some years. Each year, specific recommendations for spring and summer–autumn flows were developed by the Flaming Gorge Research Team in January and February and finalized in April with the Flaming Gorge Operations Work Group. Winter flow recommendations were similarly finalized, typically during November of each year.

Releases from Flaming Gorge Dam and flows that occurred during the research program are summarized in Appendix A. High spring flows (greater than 510 m^3/s at Jensen) occurred in 1993, 1995, and 1996. Required summer and autumn base flows were achieved consistently during the research period. Winter releases were low and stable in 1990, 1991, 1993, and 1995, as desired. Flooding concerns prompted curtailment of maximum power-plant-capacity releases in 1993 and 1995. At no time during the research period were releases made from the bypass tubes (full-bypass releases of 244 m^3/s were made in June 1997 after the Flaming Gorge Flow Recommendations Investigation had ended).

2.4 DEVELOPMENT OF INTEGRATED FLOW RECOMMENDATIONS

A Flaming Gorge Technical Integration Team (Integration Team) was assembled from members of the Flaming Gorge Research Team to integrate results of studies supporting the 1992 Biological Opinion, the 7 years (1990–1996) of additional research conducted under the Flaming Gorge Flow Recommendations Investigation, and other relevant contemporary studies in order to develop integrated flow and temperature recommendations that would benefit recovery of humpback chub, Colorado pikeminnow, and razorback sucker. Members of the Integration Team are the authors of this report.

2.4.1 Workshops and Technical Reviews

An initial task of the Integration Team was to conduct a workshop with principal investigators of the Flaming Gorge Research Group (Appendix C). The workshop was held during the week of 10 November 1997 in Salt Lake City, Utah, to discuss research findings and formulate preliminary flow and temperature recommendations on the basis of those findings. Workshop participants were divided into three technical subgroups: (1) hydrology and geomorphology, (2) Colorado pikeminnow, and (3) razorback sucker and humpback chub. These subgroups met separately, then reconvened with other subgroups and the Integration Team to discuss progress and preliminary findings.

Preliminary information on flow and temperature relationships was developed by each subgroup and presented to the group as a whole. From this information on species- and resource-specific relationships, integrated preliminary flow and temperature recommendations were developed and incorporated into a preliminary draft report that was reviewed by the principal investigators. A recurring theme of the workshop participants was the need to restore greater flow variability (annually and seasonally) in the Green River system for enhancement of temporal and spatial habitat complexity to meet the needs of the endangered fishes. It was understood that such variability would not necessarily directly benefit all species in all years, but, over the long-term, flow variability within and among years would be an important component of flow recommendations to advance recovery of the endangered fishes.

The Integration Team and principal investigators held a second workshop in Salt Lake City on 28 July 1998 (Appendix C) to discuss the preliminary draft report and recommendations contained therein. On the basis of discussions at that workshop, a draft report was prepared and subjected to additional peer review. Then the peer-review comments were used in developing a draft final report, which was submitted to the Recovery Program's Biology Committee on 18 May 1999 for review. Biology Committee comments (and those from other interested agencies and individuals) were used in developing a revised draft final report, which received additional review by the Biology Committee and approval by the Recovery Program's Management Committee on 7 April 2000.

2.4.2 Synthesis

The inherent difficulties of controlled experimentation in a large, complex ecosystem like the Green River system make it difficult to determine cause-and-effect relationships. Despite the fact that releases from Flaming Gorge Dam can be controlled to manipulate river flows and measure responses, uncontrolled variables (e.g., weather) can have large unforeseen effects. Many of the important variables of interest (e.g., flow, sediment, and temperature) are interrelated such that a change in one is accompanied by a concurrent or later change in another. Thus, any observed response cannot be attributed unequivocally to a specific variable. Antecedent flows and conditions can be important in determining fish food abundance, habitat characteristics, population size, and body condition. Stochastic variations in flow, temperature, and sediment from important tributaries, such as the Yampa River, also complicate interpretation of system responses to manipulation of flow and temperature at Flaming Gorge Dam. The range of flows evaluated during the research period was limited by meteorologic and hydrologic conditions as well as dam operational considerations. For example, the biological responses of endangered fishes to flows that were greater than power-plant capacity were not directly investigated.

Because controlled experiments were impossible to conduct in the Green River system, the Integration Team used a "lines-of-evidence" approach to develop flow and temperature recommendations for the endangered fishes. It considered the strength of evidence from all relevant studies, including those conducted in different river systems, and relied on professional judgment to determine flows and temperatures that would benefit the endangered fishes. The collection of biological-response data for all species and life stages was complicated by low fish abundance and incomplete life cycles of some species (e.g., lack of razorback sucker recruitment). Therefore, some flow recommendations were designed to restore processes (e.g., sediment transport) or habitats (e.g., inundation of floodplain areas) that have been impacted by the construction and operation of Flaming Gorge Dam and that are believed to be important in the life history of these fishes. The Integration Team also inferred that enhancing natural temporal and spatial habitat complexity through flow and temperature management would benefit the endangered species.

3 HYDROLOGY AND GEOMORPHOLOGY OF THE GREEN RIVER

Physical factors such as climate, geology, and physiography affect the distribution and abundance of organisms in and along rivers. These factors affect vegetative cover, runoff patterns, runoff rates, and volume and seasonality of river flow. Geology and vegetative cover also affect sediment dynamics and water quality within the river. Water temperature varies according to climate, season, topography, and water source. These physical factors strongly influence the life history of native species, which are adapted to the particular conditions characteristic of the watershed in which they evolved.

Physical conditions are not constant along most rivers. Large rivers typically pass through different climatic zones and areas of divergent geology. Flow patterns and geologic conditions create unevenly distributed habitats of low or high velocity within the channel and seasonally flooded habitats in areas outside the channel. High flows during the runoff period are particularly important for creating and maintaining habitats for riverine organisms, because these flow events reshape sediment deposits, scour vegetation, and flush accumulated fine sediment from the streambed. Occasional flooding of floodplain areas creates temporary, but productive, habitats and can result in substantial inputs of biomass and energy to the river for sustaining aquatic food webs.

Any discussion of the flow needs of endangered fishes in the Green River system would be incomplete without an understanding of these important physical processes. Therefore, a description of the hydrologic and geomorphic characteristics of the Green River from Flaming Gorge Dam to the Colorado River confluence is presented in this chapter. Wherever possible, an attempt is made to identify critical flow values necessary for maintenance of natural processes important to the endangered fishes both within and outside the river channel. Such processes include deposition and erosion of sand bars, creation and maintenance of low-velocity habitats, channel narrowing, vertical accretion of banks, and overbank flooding.

3.1 CHARACTERISTICS OF THE GREEN RIVER BASIN

The Green River basin, which is located in Wyoming, Colorado, and Utah, occupies a total area of 115,800 km^2. The Green River is about 1,230 km long and originates in the Wind River Range of Wyoming, flows south through Colorado and Utah, and joins the Colorado River in Canyonlands National Park (Figure 3.1). Elevations in the basin range from nearly 4,200 m in the mountainous headwaters to 1,200 m at the Colorado River confluence. The Green River is the largest tributary of the Colorado River. Nearly half of the flow of the Colorado River at its confluence with the Green River is from the Green River basin.

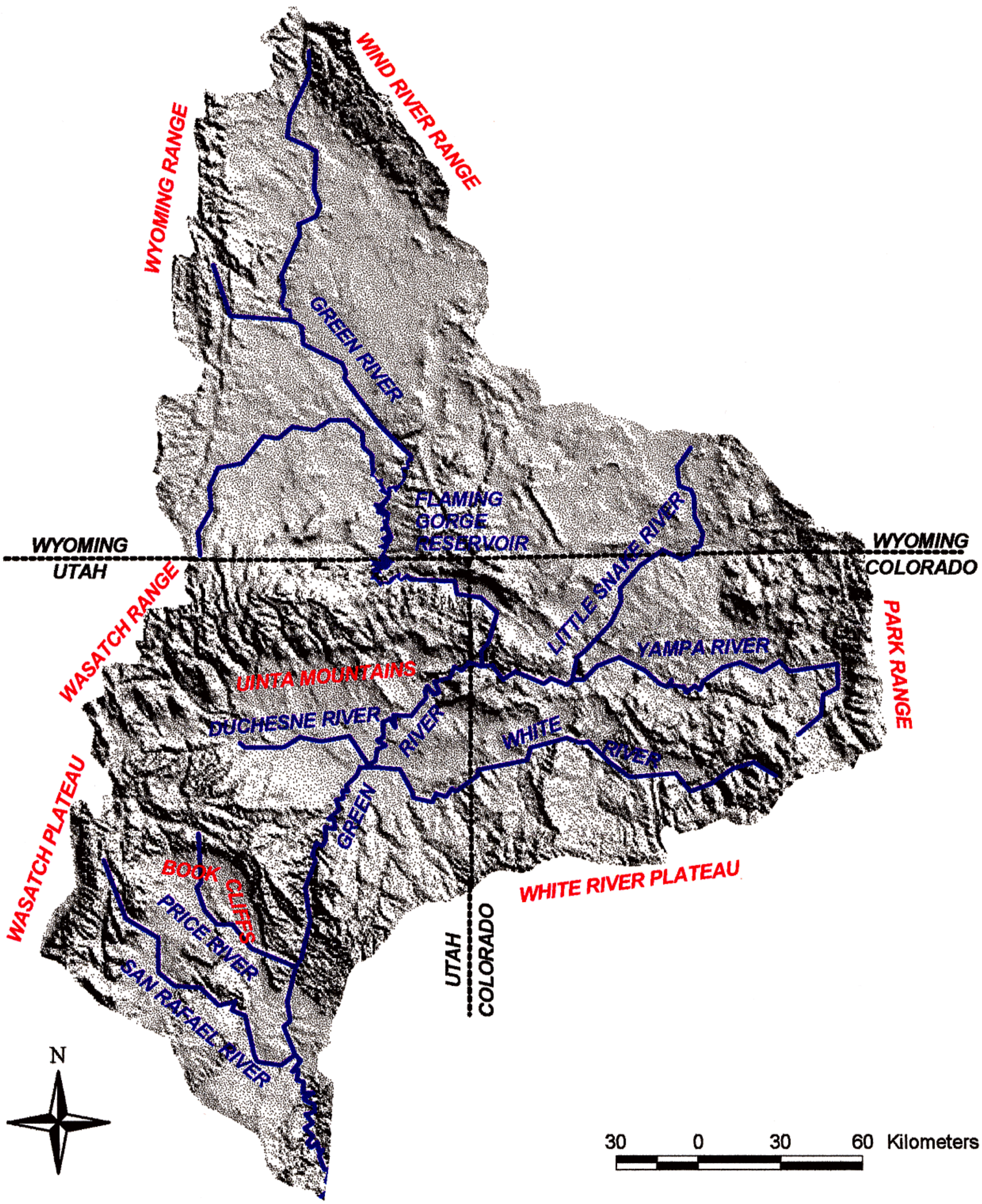


Figure 3.1.—Relief map of the Green River basin showing mountain ranges and tributaries.

Climate varies considerably across the Green River basin. In the semiarid rangelands, which make up most of the basin's area, annual precipitation is generally less than 25 cm per year. In contrast, many of the mountainous areas that rim the upper portion of the basin receive, on average, more than 100 cm of precipitation per year.

Most of the total annual stream flow in the Green River basin is provided by snowmelt. Because of this, natural flow is very high in late spring and early summer and diminishes rapidly in midsummer. Although flows in late summer through autumn can increase following rain events, natural flow in late summer through winter is generally low.

Water and sediment inputs to the Green River and its tributaries are not uniformly distributed across the basin. The principal water sources are high-elevation areas, especially in the northeast portion of the basin. Conversely, the semiarid parts of the basin at lower elevations contribute most of the sediment. Iorns et al. (1965) estimated the annual suspended sediment discharge of the Green River basin to be 25,340,910 metric tons prior to regulation. About 13% of the suspended load of the entire Green River basin was found to originate in the Green River basin upstream of the Yampa River confluence. About 6% originates from the Yampa River basin, about 26% originates from the Green River basin between the Yampa and White Rivers, and about 54% originates from the basin downstream of the White River.

Dams and reservoirs have been constructed in the basin mainly to supply water for irrigated agriculture (Table 3.1), and these facilities have resulted in reductions in Green River flow. Table 3.2 lists estimated depletions for 1998 due to water development in the basin. The largest depletion in the Green River basin occurs in the Duchesne River basin.

In addition to depleting flow volume, reservoirs modify the pattern of flow in the Green River to meet demands of irrigation, power generation, recreation, and other uses. Generally, the larger the reservoir is in relation to its watershed, the greater is its potential to modify the natural flow pattern. Of the reservoirs in the basin, Flaming Gorge, which is capable of storing approximately twice the annual inflow, has the largest effect on Green River flow patterns.

Flaming Gorge Dam has reduced the sediment load in the river downstream. This reduction results primarily from the presence of the dam (rather than operations), which traps sediment. Following completion of the dam, Andrews (1986) estimated that mean annual sediment discharge at the USGS gage near Jensen, Utah, decreased by 54% when compared with the average annual pre-dam suspended sediment load. Similarly, the decrease in mean-annual sediment load at the USGS gage near Green River, Utah, was estimated to be 48% following completion of Flaming Gorge Dam (Andrews 1986). Andrews noted that the decrease in mean annual suspended sediment load at Jensen is approximately equal to the incoming sediment load to Flaming Gorge Reservoir. At Green River, Andrews noted that the decrease in suspended sediment load following reservoir closure greatly exceeded the amount of sediment trapped in the reservoir. He concluded that sediment inflow to the Green River downstream from the Duchesne River exceeds the transport of sediment out of Reach 3.

Table 3.1.—Reservoirs of the Green River basin.

Reservoir	Live Capacity (1,000,000 m^3)	Year of Closure	River Basin
Fontenelle	425	1964	Upper Green
Big Sandy	47	1952	
Eden	16	1910	
Stateline	17	1979	
Meeks Cabin	37	1971	
Flaming Gorge	4,624	1962	
Yamcolo	11	1980	Yampa
Stagecoach	41	1988	
Lake Catamount	10	1977	
Fish Creek	4.8	1956	
Steamboat Lake	32	1965	
Elkhead	11	1974	
Strawberry	1,364	1973[a]	Duchesne
Currant Creek	19	1975	
Starvation	204	1970	
Upper Stillwater	39	1987	
Moon Lake	44	1938	
Bottle Hollow	14	1970	
Red Fleet	32	1980	
Steinaker	43	1961	
Avery Lake	9.5	1986	White
Taylor Draw	17	1983	
Scofield	81	1945	Price
Joe’s Valley	76	1966	San Rafael
Huntington North	5.2	1966	

[a] Strawberry Reservoir was originally closed in 1913. In 1973, closure of Soldier Creek Dam enlarged the reservoir to its current size.

3.2 OPERATIONS OF FLAMING GORGE DAM

Flaming Gorge Dam is located on the Green River in northeastern Utah, approximately 660 km upstream from the confluence of the Colorado and Green Rivers (Figure 2.1). Flaming Gorge Reservoir extends approximately 140 km upstream of the dam into southern Wyoming. Construction of the dam and power plant began in 1956 and was completed in 1963. Filling of the reservoir began in November 1962 and continued through 1966. Full operation began in November 1967.

In general, Flaming Gorge Dam has been operated to provide for a full reservoir while maximizing power revenue and avoiding the use of bypass tubes or the spillway. Depending on

Table 3.2.—Estimated depletions in the Green River system in 1998.

Drainage	Estimated 1998 Depletion (1,000,000 m^3)[a]
Upper Green River (upstream of Greendale, Utah)	567
Yampa River	231
White River	59
Duchesne River	585
Price River	30
San Rafael River	121

[a] Depletions were estimated by using the Colorado River Simulation System (CRSS) within the RiverWare modeling framework. Other approaches to calculating depletions may yield different results.

snowpack and monthly runoff forecasts, an appropriate winter drawdown is selected to avoid spills; it usually results in a minimum reservoir storage of approximately 987 million m^3 at a reservoir surface elevation of 1,836 m. Minimum reservoir elevations are usually achieved by 1 April each year. In years when snowpack is greater than normal, releases are increased in middle and late winter and result in additional drawdown. Following drawdown, attempts are made to refill the reservoir during spring runoff, with maximum reservoir levels usually occurring in late July each year. Releases during the remainder of the year are generally patterned to meet energy demands while meeting the constraints identified above. Peak demand for electric power occurs during summer (July through September) and winter (December through February).

Water releases from the dam for power generation have ranged from about 23 to 130 m^3/s. The maximum power-generating release[3] is constrained by the size of the turbines, whereas the lower limit (23 m^3/s) is set by an agreement with the State of Utah to maintain a high-quality trout fishery in dam tailwaters. An additional 113 m^3/s of water can be released through two steel bypass tubes (56.5 m^3/s each), and 793 m^3/s can be discharged through the spillway tunnel, but water passing through these structures produces no electric power. Although power plant releases from the dam are capable of fluctuating from 23 to 130 m^3/s to meet power commitments, actual daily operations are constrained to meet criteria presented in the 1992 Biological Opinion (USFWS 1992), usually by reducing the magnitude of (or eliminating) daily fluctuations in flow or by reducing the amount of time that peak releases are maintained.

The history of Flaming Gorge Dam operations can be divided into five phases. In the first phase, from 1963 to 1966, Flaming Gorge Reservoir was filling with water, and flows downstream of the dam were much reduced (Smith and Green 1991). The first full year of normal operations

[3] In this report, maximum power plant capacity is reported as 130 m^3/s, which is the typical historic maximum release value. With a recent system upgrade, power plant capacity releases up to 140 m^3/s are possible but depend on reservoir water-surface elevation.

began in 1967. In the second phase, from 1967 to 1978, Flaming Gorge Dam was operated with few constraints, and water releases were made from deep within the reservoir through the single outlet structure. The only constraint on releases during that period was the 23 m^3/s minimum release to establish and maintain the tailwater trout fishery (Smith and Green 1991). The dam was retrofitted with a multilevel outlet to improve water temperatures for the tailwater trout fishery in 1978. Aside from the use of the multilevel outlet structure, operations in the third phase, from 1979 to 1984, were similar to those in the previous phase (Smith and Green 1991).

An interim flow agreement was established in 1985 to change Flaming Gorge Dam releases to protect endangered fish nursery habitats in the Green River downstream of Jensen, Utah (Smith and Green 1991). The interim agreement provided for a maximum release volume of 123.4 million m^3 in August and September, with daily fluctuations at the dam between 23 and 68 m^3/s. The recommended releases were based on observations made in 1985 that indicated that "good" habitat conditions were available at lower flows. Reclamation also changed operational criteria at the dam to avoid spills, such as those that occurred in 1983 and 1984. These changes were in place in the fourth phase, from 1985 through 1992, along with numerous research releases to support preparation of the 1992 Biological Opinion.

Most recently, in the fifth phase, operations at Flaming Gorge Dam have incorporated recommendations of the 1992 Biological Opinion, including providing flows needed for the Flaming Gorge Flow Recommendations Investigation (Section 1.3). Flows recommended in the Biological Opinion were intended to restore a more natural hydrograph and protect nursery habitats of endangered fishes downstream of the Yampa River confluence. The Biological Opinion called for a full power-plant-capacity release (133 m^3/s) each spring and included recommendations for target flows in summer and autumn (31 to 51 m^3/s), with fluctuations in flow at Jensen constrained to 25% of target flow to protect nursery habitats in this reach. Releases during the winter were held steady once an ice cover formed in the Jensen area (generally December through February) to protect endangered fish habitats.

3.3 DESCRIPTION OF GREEN RIVER REACHES DOWNSTREAM OF FLAMING GORGE DAM

The longitudinal profile of the Green River downstream from Flaming Gorge Dam includes steep and flat segments, and the gradients of these segments do not systematically decrease in a downstream direction (Figure 3.2). In general, low-gradient reaches of the river have sandy substrates, but segments with steeper gradients have gravel or cobble substrates (Schmidt 1996). For this report, the Green River is divided into three reaches delimited by major tributaries (Figure 2.1).

Reach 1, between Flaming Gorge Dam and the Yampa River confluence, is about 104 km in length (Figure 2.1). Flow in this reach is measured at the USGS gage near Greendale, Utah. Reach 1 is straight to meandering and, with the exception of Browns Park, tightly confined by the

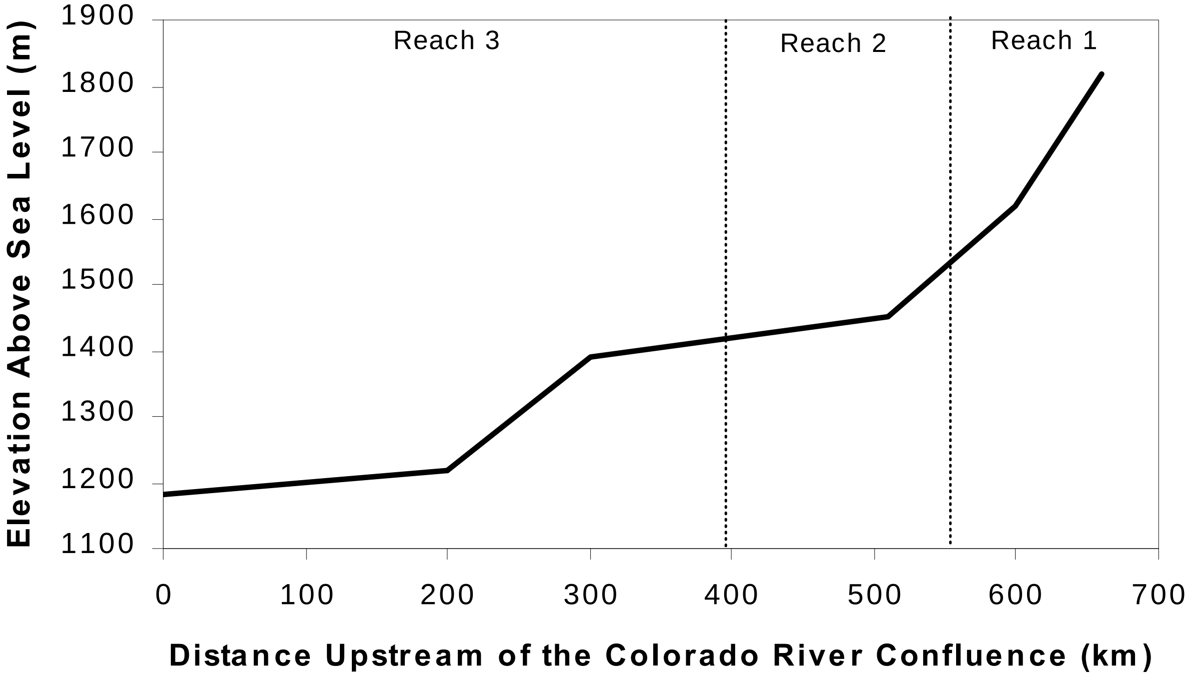


Figure 3.2.—Longitudunal profile of the Green River between the Colorado River confluence and Flaming Gorge Dam.

adjacent steep-walled canyon topography. Except for usually minor flow contributions from tributary streams, flow in Reach 1 is completely regulated by Flaming Gorge Dam. The mean annual discharge (about 60.3 m^3/s) has not been affected by Flaming Gorge Dam operations, but the pattern of flow has been changed. Prior to regulation, the seasonal flow pattern for Reach 1 featured high spring flows and low summer, autumn, and winter base flows. Releases for power generation have resulted in relatively uniform monthly release volumes but significant within-day variation when compared with the pre-dam condition (Section 3.4).

Downstream from Flaming Gorge Dam, the Green River flows through Red Canyon for about 19 km. This portion of Reach 1 has been armored since construction of the dam, and the relatively coarse bed material inhibits further downcutting of the riverbed. Because the dam eliminates sediment contributions from upstream reaches, sediment-source areas for Red Canyon are limited to small tributary streams (e.g., Red

Green River Reach Designations Used in This Report

Reach 1 – Flaming Gorge Dam to the Yampa River confluence (river kilometer [RK] 555.1 to 659.8). Flow in this reach is measured at the USGS gage near Greendale, Utah.

Reach 2 – Yampa River confluence to White River confluence (RK 396.2 to 555.1). Flow in this reach is measured at the USGS gage near Jensen, Utah.

Reach 3 – White River confluence to Colorado River (RK 0 to 396.2). Flow in this reach is measured at the USGS gage near Green River, Utah.

Creek), which contribute sediment during localized runoff events. The channel slope is about 0.002 in this part of Reach 1.

Downstream from Red Canyon, the Green River flows through the wide alluvial valley of Browns Park for approximately 51 km before entering Lodore Canyon. The channel in Browns Park ranges from meandering to braided and is relatively flat, with a gradient of about 0.0008. The size of bed material decreases through this segment, and in the lower 18 km of Browns Park, the entire channel has a sand bed. Bank erosion is a common source of sediment in this segment of the river.

In Lodore Canyon, the river channel is a series of linked straight reaches constrained by steep rock walls. The bends that link the straight reaches are often coincident with geologic structures (Grams and Schmidt 1999). The dominant channel features of this portion of Reach 1 are debris fan-eddy complexes located at the mouths of tributary streams (see Section 3.6.1.2). The channel gradient through the canyon is relatively steep (about 0.003).

Reach 2, between the Yampa River and White River confluences, is about 158 km in length (Figure 2.1). Flow in this reach is recorded at the USGS gage near Jensen, Utah, about 46 km downstream from the Yampa River confluence. This is a relatively long, meandering reach with numerous subsegments having varying geomorphic characteristics. Reach 2 exhibits a more natural flow and sediment regime than Reach 1 because of inputs from the relatively unregulated Yampa River. Despite this fact, there has been a 26% decrease in the magnitude of the mean annual flood at the Jensen gage since closure of Flaming Gorge Dam (Section 3.4). The Yampa River adds about 1.7 million metric tons of sediment to the Green River on a yearly basis. Mean annual discharge of the Yampa River is about 56.6 m^3/s.

Downstream from the Yampa River confluence at Echo Park, the Green River flows through canyons and open alluvial valleys. Whirlpool Canyon extends for about 17 km below the confluence and has a channel slope of about 0.002. Numerous rapids are located in this portion of Reach 2, and debris fan-eddy complexes are common. Leaving Whirlpool Canyon, the river flows through Island Park, Rainbow Park, and Little Rainbow Park for about 11 km. Multiple channels and vegetated islands are common in these open areas, and the channel gradient is relatively low (about 0.0009). As it does in Browns Park, sand makes up most of the channel bed in these areas.

Downstream from Rainbow Park, the Green River enters 11-km-long Split Mountain Canyon, where the river gradient is steeper (about 0.0038). From Split Mountain Canyon, the Green River meanders through the broad valley of the Uinta basin for about 114 km to the confluences of the Duchesne and White Rivers. Channel pattern is predominantly restricted meanders in the valley (Section 3.6.1), and the gradient ranges from 0.0009 in the 15 km below Split Mountain to about 0.0003 for the rest of Reach 2. Bed materials range from cobbles to sand, and vegetated and unvegetated islands are common. The Uinta basin portion of Reach 2 contains important nursery habitats for the Colorado pikeminnow (in-channel backwaters) and razorback sucker (inundated floodplains; Sections 4.2 and 4.3).

Reach 3, between the White River and Colorado River confluences, is about 394 km in length (Figure 2.1). The White and Duchesne Rivers at the upper end of Reach 3 add considerable sediment (about 4.4 million metric tons per year) to the Green River. A portion of the flow of the Duchesne River is diverted out of the Green River basin; the combined mean annual discharge of the White and Duchesne Rivers is about 31 m^3/s. Before entering Gray and Desolation Canyons in Reach 3, the Green River meanders through the Unita basin and has a low gradient (about 0.0002). Numerous sandbars can be found in this portion of the reach at low flow, and low-elevation floodplain areas are prominent.

In Gray and Desolation Canyons, gravel bars are abundant, and many of the banks are composed of coarse debris-flow material or talus. Recirculating eddies are also prevalent, and there are many regions of stagnant flows in these canyons. Three geomorphic divisions occur in the 151-km portion of Reach 3 from Sand Wash through Gray Canyon: (1) an upstream division with a very low channel gradient and wide channel width; (2) a middle section with steep gradients and abundant debris fans; and (3) a lower section with a moderate gradient and very narrow channel widths. The average channel gradient through these canyons is about 0.001, and the bed material ranges from sand in the upper portion and in the recirculating eddies to cobbles and boulders in the riffles and rapids formed by debris fans. The Price River is the principal tributary in this part of Reach 3.

Downstream from Gray Canyon, the river flows through a broad valley for approximately 62 km. The channel pattern is primarily restricted meanders (Section 3.6.1.1), although straight channels occur in some areas. The channel gradient is about 0.0004, and the bed material ranges from sand to gravel and cobble. The San Rafael River is the largest tributary in this part of Reach 3.

The lower 148 km of the Green River flows through Labyrinth and Stillwater Canyons and has a sinuous river channel with a relatively mild gradient of about 0.0002. Bed material is predominantly sand in this portion of Reach 3, with numerous emergent sand bars at low flow.

3.4 FLOWS IN THE GREEN RIVER DOWNSTREAM OF FLAMING GORGE DAM

This section presents a discussion of annual, seasonal, and daily variability in flow in the Green River and effects of depletions and dam operations on these flows. This information is necessary to understand changes that have occurred in flows and how these changes affect ecological conditions and endangered fish populations. Flow data are based on USGS flow gages in the Green River and its tributaries (Figure 3.3). Table 3.3 lists significant gages and the period of record for which data have been collected at those gages. Numerous other gages exist in the Green River basin closer to the mountainous headwaters. Data from Flaming Gorge and Fontenelle Dams (on reservoir storage, inflow, releases, etc.) were also used in some analyses.

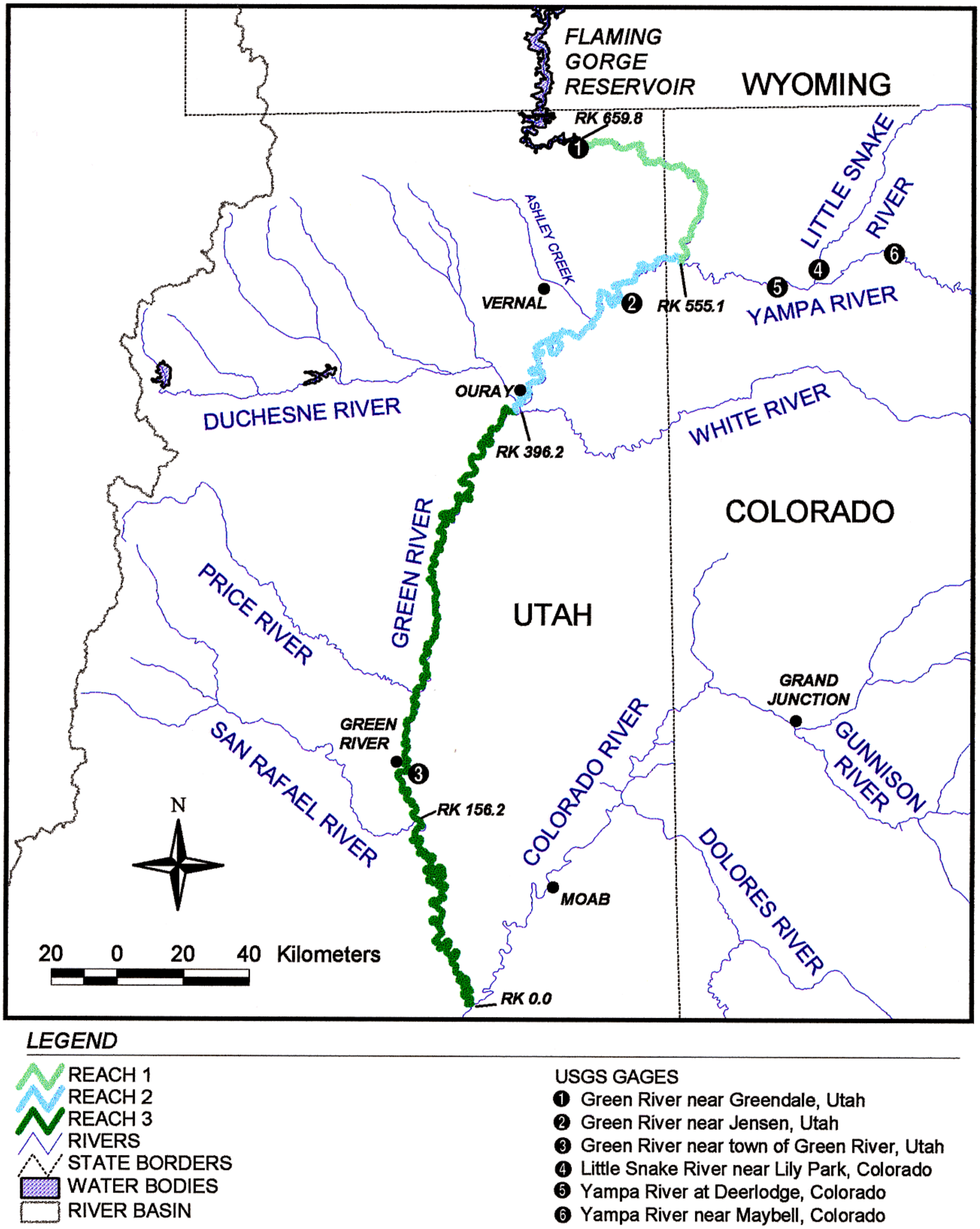
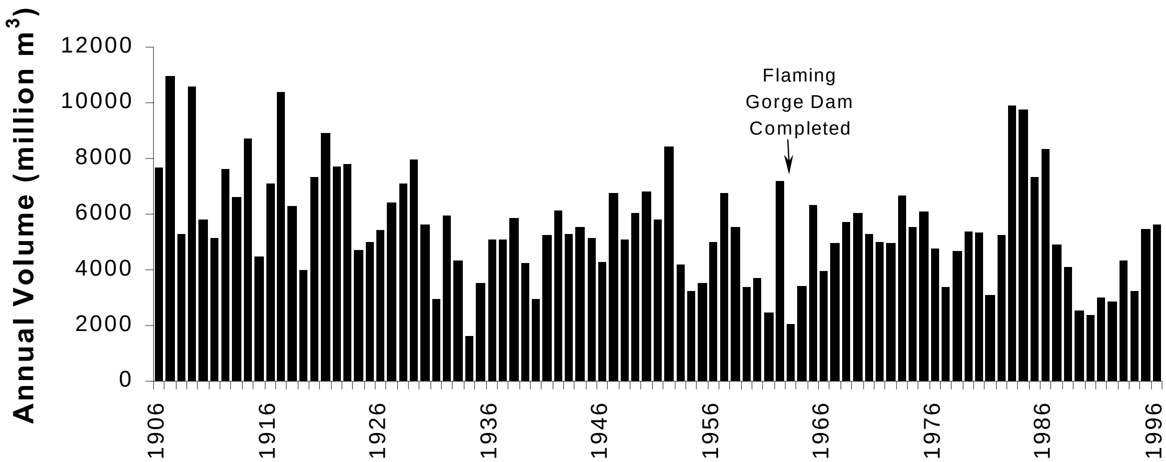


Figure 3.3—Locations of the USGS flow gages in the Green River study area.

Table 3.3.—USGS stream flow gages in the Green River system and their periods of record.

Gage	Period of Record
Green River near Greendale, Utah	October 1950 to present
Little Snake River near Lily, Colorado	June to August 1904 October 1921 to present
Yampa River near Maybell, Colorado	April 1904 to October 1905 June 1910 to November 1912 April 1916 to present
Green River near Jensen, Utah	October 1903 to December 1904 June to August 1905 March to September 1906 July to October 1914 August to December 1915 October 1946 to present
Duchesne River near Randlett, Utah	October 1942 to present
White River near Watson, Utah	April 1904 to October 1906 May to November 1918 April 1923 to September 1979 October 1985 to present
Price River near Woodside, Utah	December 1945 to October 1992
San Rafael River near Green River, Utah	May 1909 to September 1918 September 1919 to July 1920 October 1945 to present
Green River at Green River, Utah	October 1894 to October 1899 October 1904 to present

Figure 3.4 shows annual volumes and peak flows at the USGS gage near Green River, Utah. Flows in the river reflect changes in watershed conditions including the historic occurrence of wet and dry cycles, dam construction, and trans-basin diversions (Allred 1997; Allred and Schmidt 1999). Effects of weather change can be seen in the figure by comparing the magnitude of annual volumes from 1906 through 1929 with annual volumes thereafter. The average annual volume of flow was 7,040 million m^3 during 1906–1929, whereas during 1930–1996, the average annual volume of flow decreased 29% to 4,990 million m^3. Three extended periods of drought can be observed in the historic record: 1931–1940, 1953–1964, and 1987–1994. During the mid-1980s, there were four consecutive wet years (1983–1986).



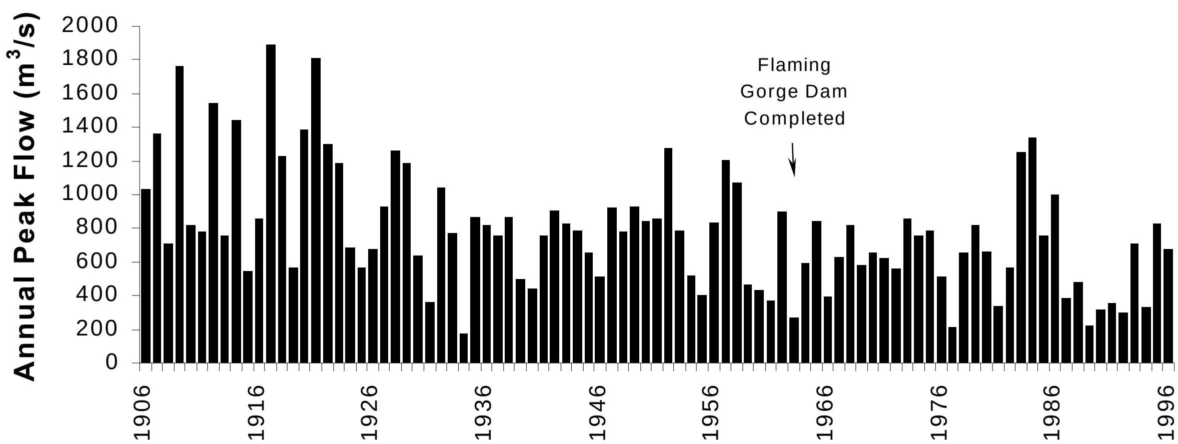


Figure 3.4.—Annual volumes and peak flows of the Green River at the USGS stream gage near Green River, Utah, 1906–1996.

Prior to closure of Flaming Gorge Dam, annual peak flows at Green River, Utah, averaged 926 m^3/s. After 1963, peak flows at Green River averaged 632 m^3/s. The highest peak on record for the Green River gage was 1,929 m^3/s on 27 June 1917. Peak discharge at Green River exceeded 1,700 m^3/s in 1897, 1909, 1917, and 1921 (Schmidt 1994). The lowest annual peak on record at Green River was 183 m^3/s on 17 May 1934.

Figure 3.5 depicts spring peak flows in the Green River near Jensen, Utah, from 1947 to 1996, with the component contributions of the Green and Yampa rivers indicated. Prior to the closure of Flaming Gorge Dam, peak flows in the Green River were higher, and the relative contributions of the Green and Yampa Rivers in producing the spring peak were very similar. Following closure of the dam, the pattern changed. Mean annual peak flows were reduced, and the

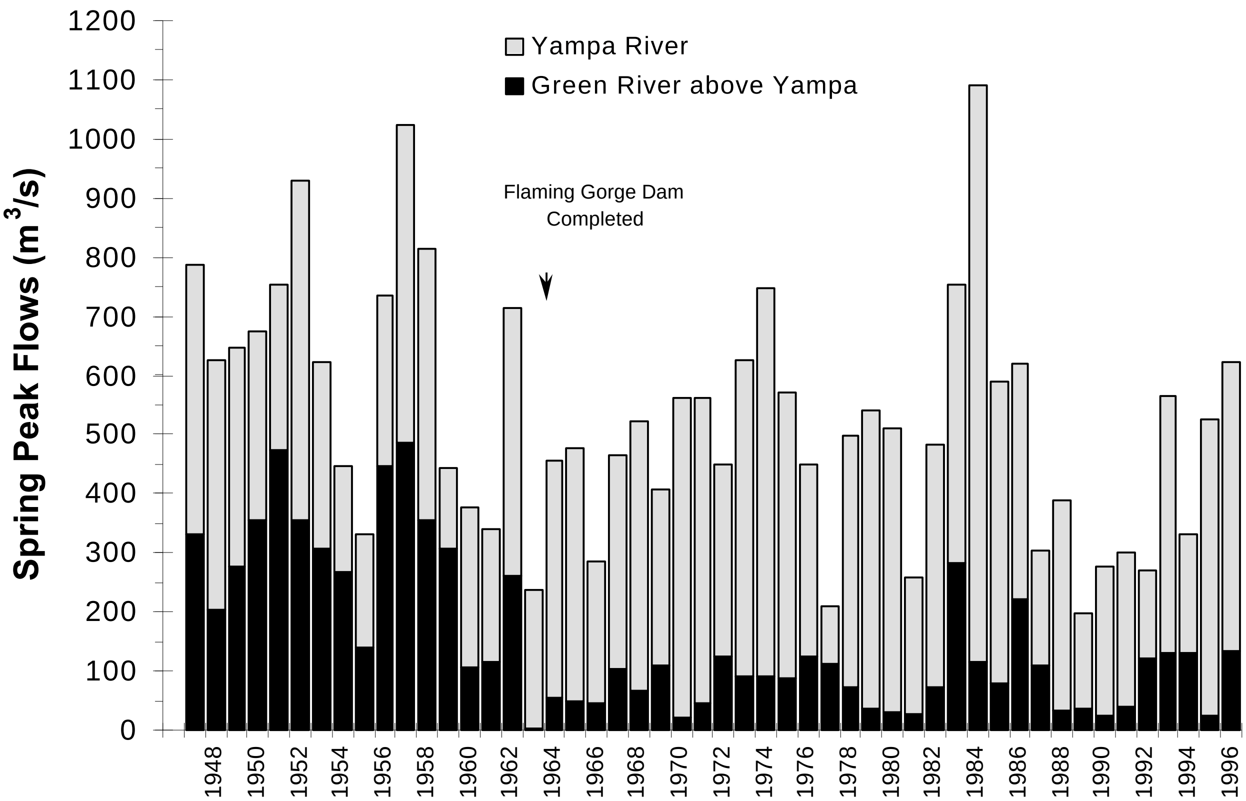


Figure 3.5.—Contributions of the upper Green River and Yampa River to spring peak flows at the USGS stream gage near Jensen, Utah, 1947–1996.

relative contribution of the upper Green River to the peak flow decreased. For the period of 1947 to 1962, the mean annual peak at Jensen was 680 m^3/s. Since 1963, the mean annual peak has been reduced to 493 m^3/s (FLO Engineering, Inc. 1997). Despite this reduction in the mean annual peak flow, the highest peak on record at Jensen (1,133 m^3/s) occurred on 18 May 1984. The lowest annual peak on record at Jensen was 201 m^3/s on 26 April 1989.

This natural year-to-year variability in flows makes it difficult to make pre- and post-dam comparisons to illustrate the effects of Flaming Gorge Dam operations on flows. To understand the effects of operations, a simulated time series of daily unregulated flow was developed for this report (see Appendix A for a description of the approach used) and compared with gauged flow data during the same period. Unregulated flows for the period 1963 to 1996 were generated by using numeric modeling techniques in which the effects on flows from operating Flaming Gorge and Fontenelle Dams were removed and propagated to the Greendale, Jensen, and Green River gages. These modeled unregulated flows are used in this section to characterize the hydrology of the upper Green River basin and quantify effects of dam operations on Green River flows.

3.4.1 Seasonal Distribution of Green River Flows

Flow in the Green River is dominated by snowmelt; consequently, there was a great deal of seasonal variability in the unregulated flow regime. To quantify how this variability has been affected by regulation, a comparison was made between the monthly distribution of regulated and unregulated flow in the three reaches; data used were from 1963 to 1996. These data are presented in Figure 3.6, and the percentage change in mean monthly flow due to regulation is presented in Table 3.4.

Regulation has resulted in a reduction of flows from April through July and an increase in flows from August through March. Reach 1, whose flow is dominated by releases from Flaming Gorge Dam, has been most affected. The effects of regulation have been reduced in Reaches 2 and 3, since intervening tributaries, especially the Yampa River, contribute flows whose seasonal distributions have been less affected by regulation. Nevertheless, flow variability in the system has been reduced in all three reaches.

3.4.2 Peak Flows in the Green River

Regulation has resulted in a substantial reduction in the magnitude of spring peak flows. Before construction of Flaming Gorge Dam, median spring peak flows were about 330 m^3/s (Figure 3.7), but they were reduced to about 85 m^3/s after the dam was built. Only five occurrences of releases greater than 200 m^3/s have occurred since construction of the dam was completed in 1962 (1983, 1984, 1986, 1997, 1999). Daily time-series data for 1963 to 1996 were used[4] to compare measured regulated peak flows to estimated unregulated peak flows. For all but measured flows at the Greendale gage, log Pearson III distributions were created to enable comparisons of specific exceedance periods. For flows at Greendale, effects of Flaming Gorge Dam preclude the use of a log Pearson III distribution. For these data, a distribution was created by ranking values.

The frequency of high peak flows has been reduced significantly by regulation (Figure 3.8). The discrepancy between regulated and unregulated flows is greatest in Reach 1, with effects of regulation diminishing downstream. Table 3.5 presents the same data, showing specific flow values and recurrence intervals for the corresponding exceedance levels. At the Jensen gage, the median peak flow is 669 m^3/s without regulation and 448 m^3/s with regulation. At the Green River gage, the median peak flow has been reduced from 788 to 575 m^3/s. The percent reduction in peak flow between unregulated and regulated conditions is shown in Table 3.6.

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[4]Ideally, instantaneous peak flows would have been used in this analysis, but the simulation of unregulated instantaneous peak flows is not feasible. However, the difference between daily average peak flows and instantaneous peak flows is not great. From 1963 to 1996, the instantaneous peak flow at the Jensen gage was calculated to be only 3.8% higher than the daily average peak flow; consequently, daily average peaks adequately convey the character of peak flows in the Green River basin.

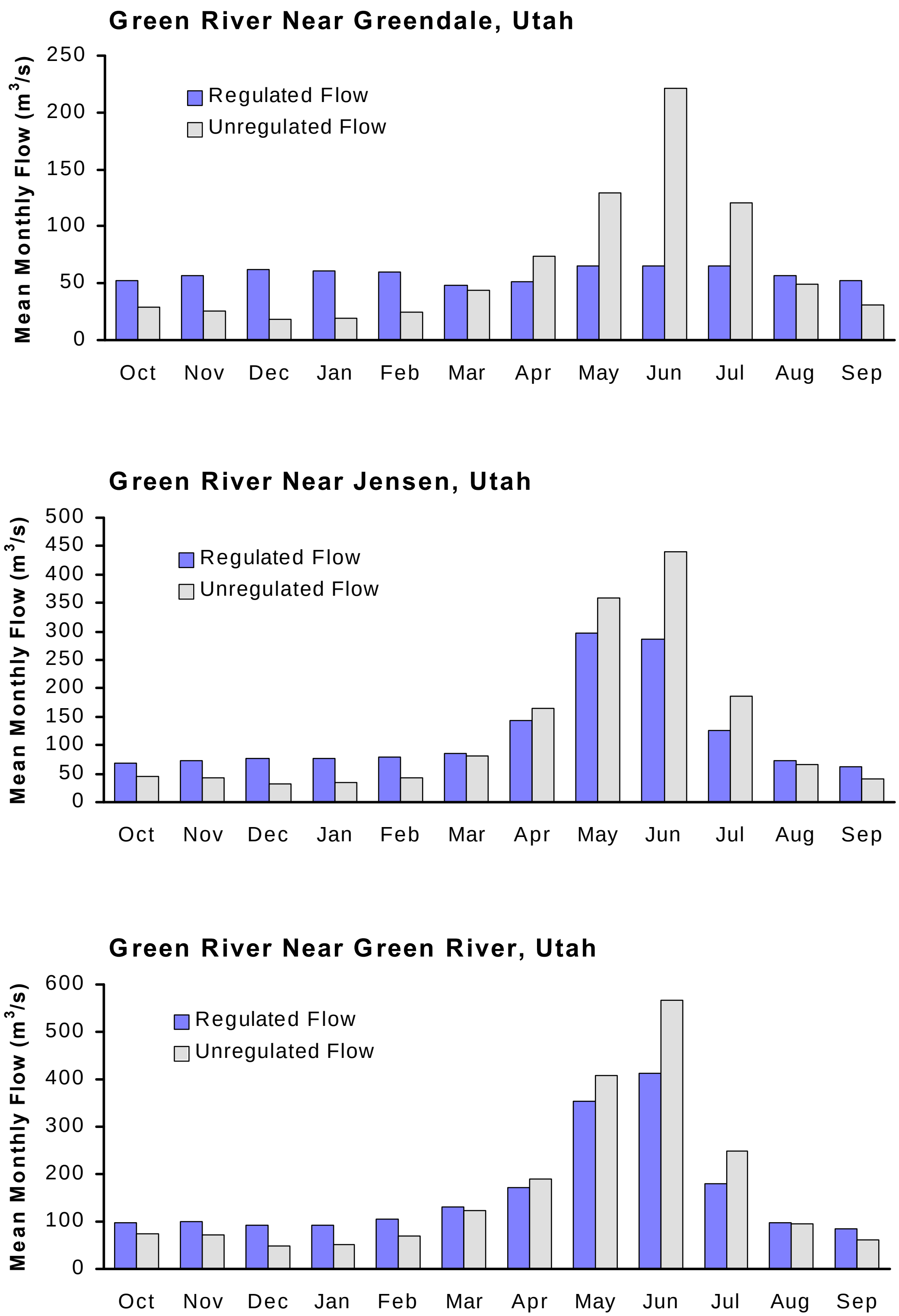
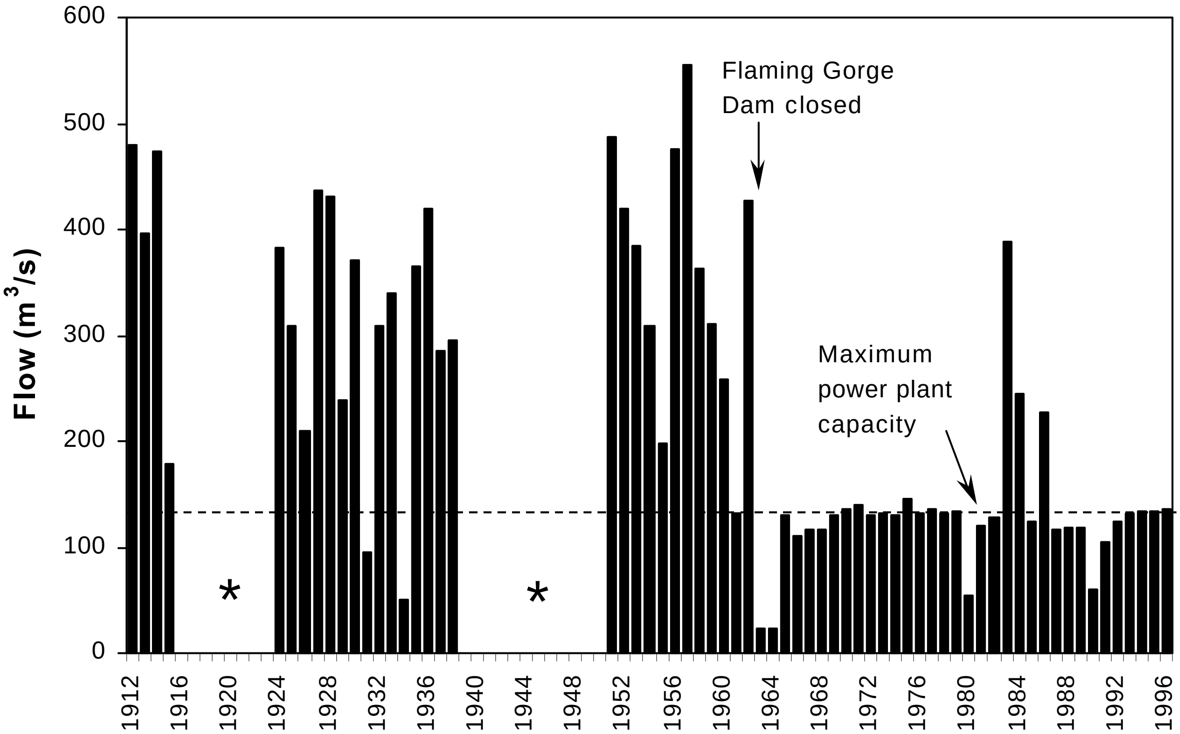


Figure 3.6.—Mean monthly regulated and unregulated flows in the Green River, 1963–1996.

Table 3.4.—Percent change in mean monthly flow of the Green River due to regulation.

River Reach/Gage	Percent Change in Mean Flow Due to Regulation											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Reach 1/Greendale	+80	+120	+246	+214	+143	+8	-30	-50	-70	-46	+16	+72
Reach 2/Jensen	+52	+71	+140	+121	+82	+6	-13	-17	-35	-32	+10	+54
Reach 3/Green River	+31	+39	+89	+83	+53	+6	-10	-13	-27	-28	+2	+34



Flow records are from the following locations: 1912 to 1915, near Bridgeport, Utah (upper Browns Park, gage 09235000); 1924 to 1938, near Linwood, Utah (submerged by Flaming Gorge Reservoir, gage 09230500); 1951 to 1996, near Greendale, Utah (gage 09234500); asterisks denote break in the record.

Figure 3.7.—Peak annual flow of the Green River near present-day Flaming Gorge Dam in pre- and post-dam periods.

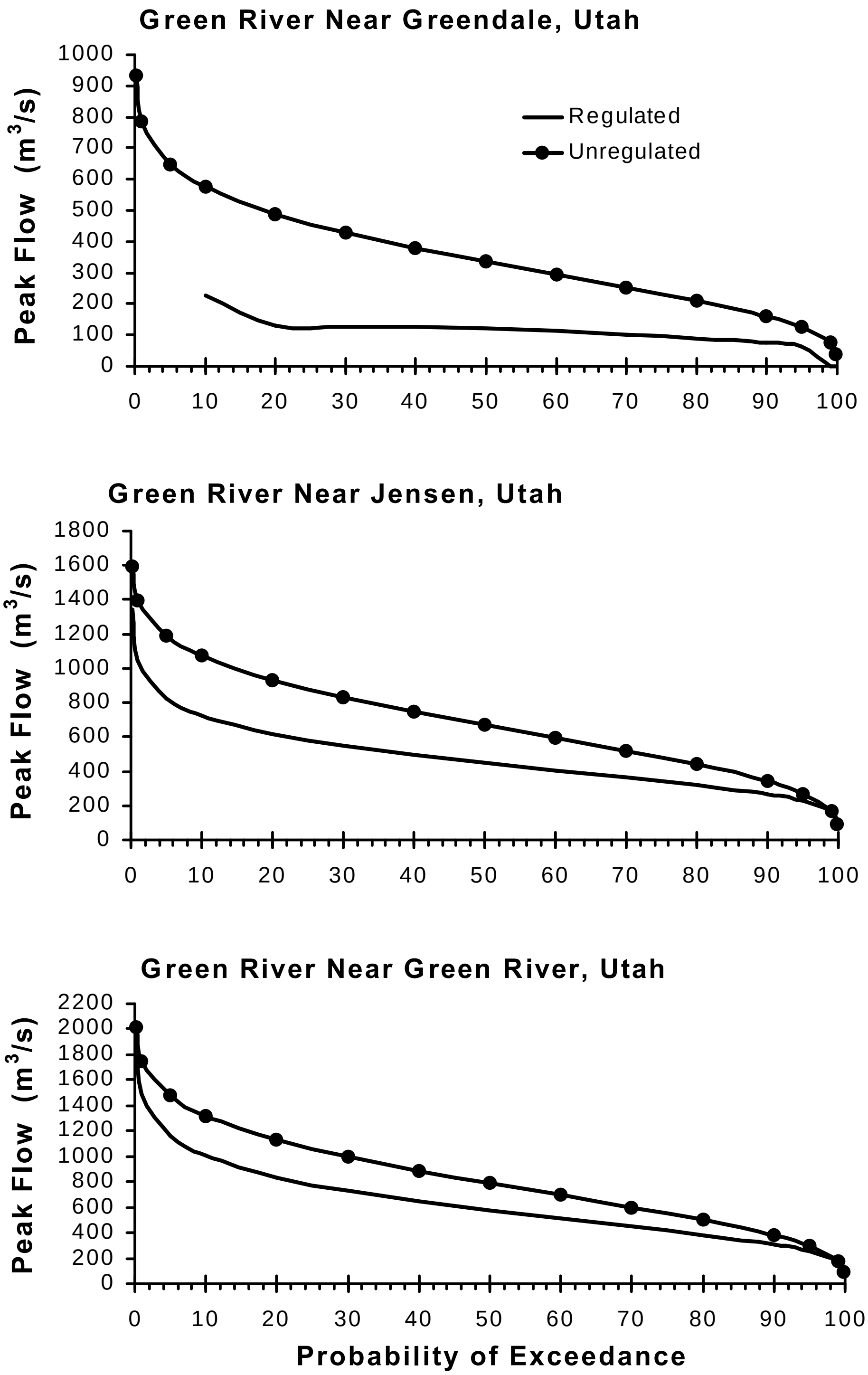


Figure 3.8.—Peak flow exceedance curves for regulated and unregulated flows in the Green River, 1963–1996.

Table 3.5.—Probabilities of exceedance for regulated and unregulated flows of the Green River at the USGS stream gages near Jensen (Reach 2) and Green River, Utah (Reach 3), 1963–1996.

Probability of Exceedance (%)	Recurrence Interval Years	Flow at Jensen Gage (m^3/s)		Flow at Green River Gage (m^3/s)	
		Regulated	Unregulated	Regulated	Unregulated
50	2	448	669	575	788
20	5	618	934	836	1,132
10	10	727	1,076	1,003	1,321
5	20	827	1,192	1,158	1,477
1	100	1,045	1,396	1,495	1,753

Table 3.6.—Percent reduction in annual peak flows of the Green River due to regulation at various exceedance values.

River Reach/Gage	% Flow Reduction Due to Regulation at Various % Exceedance Values								
	10	20	30	40	50	60	70	80	90
Reach 1/Greendale	-61	-73	-70	-67	-63	-61	-60	-58	-52
Reach 2/Jensen	-32	-34	-34	-34	-33	-32	-30	-28	-23
Reach 3/Green River	-24	-26	-27	-27	-27	-26	-25	-23	-19

The duration and timing of peak flows have also been reduced by regulation. Unregulated flows of 475 and 575 m^3/s are exceeded at the Jensen gage 8% and 4% of the time, respectively (Figure 3.9). With regulation, however, these two flows are exceeded only 3% and 1% of the time. On average, peak flows now occur earlier in the year than they did before regulation. For both Reach 2 and Reach 3, regulated peak flows generally occur about a week earlier than unregulated peak flows (Table 3.7).

3.4.3 Base Flows in the Green River

Approximately 70% of the annual natural flow of the Green River occurs between April and July as a result of melting snow. During the remainder of the year, natural flows are generally low.

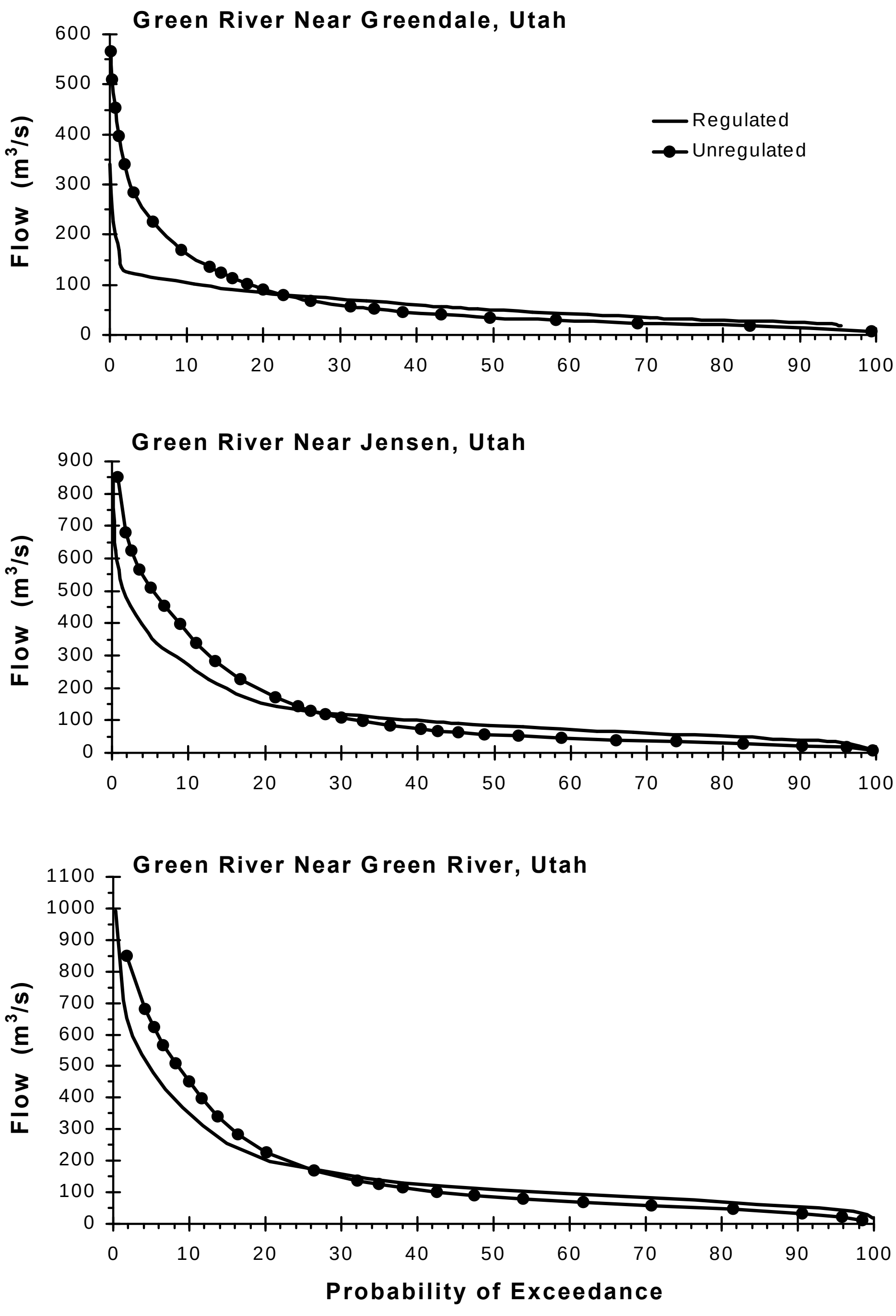


Figure 3.9.—Flow duration exceedance curves for regulated and unregulated peak flows in the Green River, 1963–1996.

Table 3.7.—The effect of regulation on mean date of peak flow at USGS stream gages on the Green River.

Gage	Regulation Condition	Mean Date of Peak Flow
Greendale	Unregulated	9 June
	Regulated	---
Jensen	Unregulated	3 June
	Regulated	27 May
Green River	Unregulated	6 June
	Regulated	31 May

In this report, flow in August through February is referred to as base flow. The source of unregulated base flows is predominately groundwater, with occasional augmentation by rain events and snowmelt.

As discussed in Section 3.4.1, regulation has produced base flows that are considerably higher than would have occurred without regulation. Flow duration curves that compare regulated and unregulated flows for all three reaches are displayed in Figure 3.9. Regulation has reduced the percentage of time that flows are either very high or very low. This result can be clearly seen by comparing flow-duration data at the Jensen gage. Without regulation, flows at Jensen are less than 28 m^3/s about 17% of the time. With regulation, flows at Jensen are less than 28 m^3/s only 3% of the time. Regulation and the establishment of the 23-m^3/s minimum release from Flaming Gorge Reservoir (see Section 3.2) has resulted in higher base flows.

The date when base flow is reached varies according to the hydrologic conditions. Base flows are reached at Jensen by the first of August in years with average conditions, by late June in dry years (90% exceedance), and by late August in wet years (10% exceedance).

Although unregulated base flows in the Green River are generally considered stable, variability in flows occurs during the base-flow period even without hydropower-induced fluctuations. Variability can occur at a number of different time scales, including between years, within years, between days, and within days. Each type of variability can have different effects on geomorphic and ecological processes (e.g., between- and within-year variability can affect vegetation establishment on low-elevation sand bars; between- and within-day variability can affect conditions within backwaters used by the endangered fishes). The level of variability in the Green River basin at each of these time scales is discussed below.

Mean daily flows at the Jensen gage during the base-flow period were used to determine the level of flow variability between and within years. Between-year differences are largely related to annual hydrologic conditions, and, as would be expected, base flow under wet and moderately wet conditions is greater than base flow under average or moderately dry to dry conditions (Table 3.8).

Within-year variability expressed here as the median within-year coefficient of variation[5] (CV) among mean daily flows was considerably higher during the pre-dam period (1946 to 1962) than the post-dam period (1963 to 1996; Table 3.8). For the August through February base-flow period, the median CV was approximately 48% pre-dam and 25% post-dam. Mean daily flows at the Jensen gage during 1947 to 1950 base-flow periods are plotted in Figure 3.10 to illustrate the variability that occurred prior to construction of Flaming Gorge Dam. Variability during both pre-dam and post-dam periods was less in the winter (December through February) than in the summer and autumn (August through November). During the pre-dam period, the level of variability within a year was dependent on annual hydrologic conditions, with lower variability observed in drier years (Table 3.8).

Between-day variability also was assessed on the basis of mean daily flow values at the Jensen gage. The percent change in flow between days was calculated by finding the difference between flow values for day *t* and the previous day and dividing the result by the mean daily flow on day *t*. Median between-day differences during the base-flow period were about 3% (range, 0 to 68%) pre-dam and 5% (range, 0 to 139%) post-dam.

To determine natural levels of *within-day flow variability*, instantaneous flow measurements are needed. These data are not readily available because the USGS archives flow data as mean daily values. Only the most recent data are available as instantaneous flow values. For this study, instantaneous unregulated flow measurements were not available for the Jensen gage. Consequently, values at the Deerlodge gage on the essentially unregulated Yampa River were used instead to estimate natural levels of within-day variability during the base-flow period in the Green River basin. Instantaneous flow values from this gage for the 1997–1998 and 1998–1999 base-flow periods are plotted in Figure 3.11. These graphs illustrate the degree of variability that occurs within each year and within days. Statistical analyses of these data indicate that the median percentage change within days (calculated as daily maximum minus daily minimum divided by the mean daily flow) is 9.6% (range, 0 to 94.4%); the mean percent within-day change is 14.3%.

The degree of variability in flows within the base-flow period in the Green River system are higher than values that have been inferred for this system. Much of the within-year variability can be attributed to weather patterns and events. The within-day variability may be attributed to daily freeze-thaw cycles in higher-elevation snowpacks and subsequent variation in runoff and groundwater discharge. The observed level of variability in the Green River system contrasts with "natural" levels of variability that have been suggested for this system by Stanford (1994). In his review of the 1992 Biological Opinion, Stanford suggested that base flows should be stable and limited to pre-regulation conditions "as reflected in the Yampa River hydrographs over the period

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[5]The CV is calculated as the standard deviation divided by the mean and is expressed as a percentage. The CV allows comparison of within-year variation among years that have different mean-flow values.

Table 3.8.—Mean base flows and base-flow variability as measured by coefficient of variation (CV)[a] at the USGS stream gage near Jensen, Utah, 1946–1996.

Hydrologic Condition	Period of Record (1946–1996) Number of Years	Period of Record (1946–1996) Mean Daily Flow (m^3/s)	Period of Record (1946–1996) Median within-Year CV for Mean Daily Flow	Pre-Dam (1946–1962) Number of Years	Pre-Dam (1946–1962) Mean Daily Flow (m^3/s)	Pre-Dam (1946–1962) Median within-Year CV for Mean Daily Flow	Post-Dam (1963–1996) Number of Years	Post-Dam (1963–1996) Mean Daily Flow (m^3/s)	Post-Dam (1963–1996) Median within-Year CV for Mean Daily Flow
ENTIRE BASE-FLOW PERIOD (AUGUST THROUGH FEBRUARY)									
Wet	5	110.9	29.0%	2	56.0	65.8%	3	113.5	28.4%
Moderately wet	10	88.4	24.1%	4	54.2	52.0%	6	93.7	24.1%
Average	20	58.5	27.8%	5	36.7	47.9%	15	72.6	27.8%
Moderately dry	10	36.8	42.9%	4	29.0	40.5%	6	50.5	21.8%
Dry	5	26.3	28.6%	1	26.3	27.6%	4	35.0	19.9%
All years	50	62.2	28.8%	16	39.5	47.9%	34	72.8	24.5%
SUMMER AND AUTUMN BASE-FLOW PERIOD (AUGUST THROUGH NOVEMBER)									
Wet	5	110.3	24.0%	2	70.1	51.6%	3	113.9	27.1%
Moderately wet	10	83.2	24.6%	4	59.2	39.1%	6	91.4	22.5%
Average	20	58.6	26.6%	5	42.4	43.6%	15	66.0	23.9%
Moderately dry	10	40.0	28.8%	4	32.1	42.4%	6	50.6	23.8%
Dry	5	26.1	30.8%	1	28.2	30.1%	4	32.3	21.6%
All years	50	61.7	26.6%	16	45.3	40.7%	34	69.4	24.0%
WINTER BASE-FLOW PERIOD (DECEMBER THROUGH FEBRUARY)									
Wet	5	118.8	12.8%	2	51.5	88.7%	3	120.0	12.4%
Moderately wet	10	95.0	20.7%	4	37.9	27.9%	6	103.4	22.4%
Average	20	57.1	21.0%	5	30.1	24.8%	15	78.5	21.0%
Moderately dry	10	31.4	24.1%	4	24.1	31.5%	6	50.8	20.2%
Dry	5	22.4	18.8%	1	19.7	18.4%	4	37.0	14.0%
All Years	50	62.3	20.5%	16	31.7	27.9%	34	78.0	19.4%

[a]The coefficient of variation is calculated as the standard deviation divided by the mean and is expressed as a percentage.

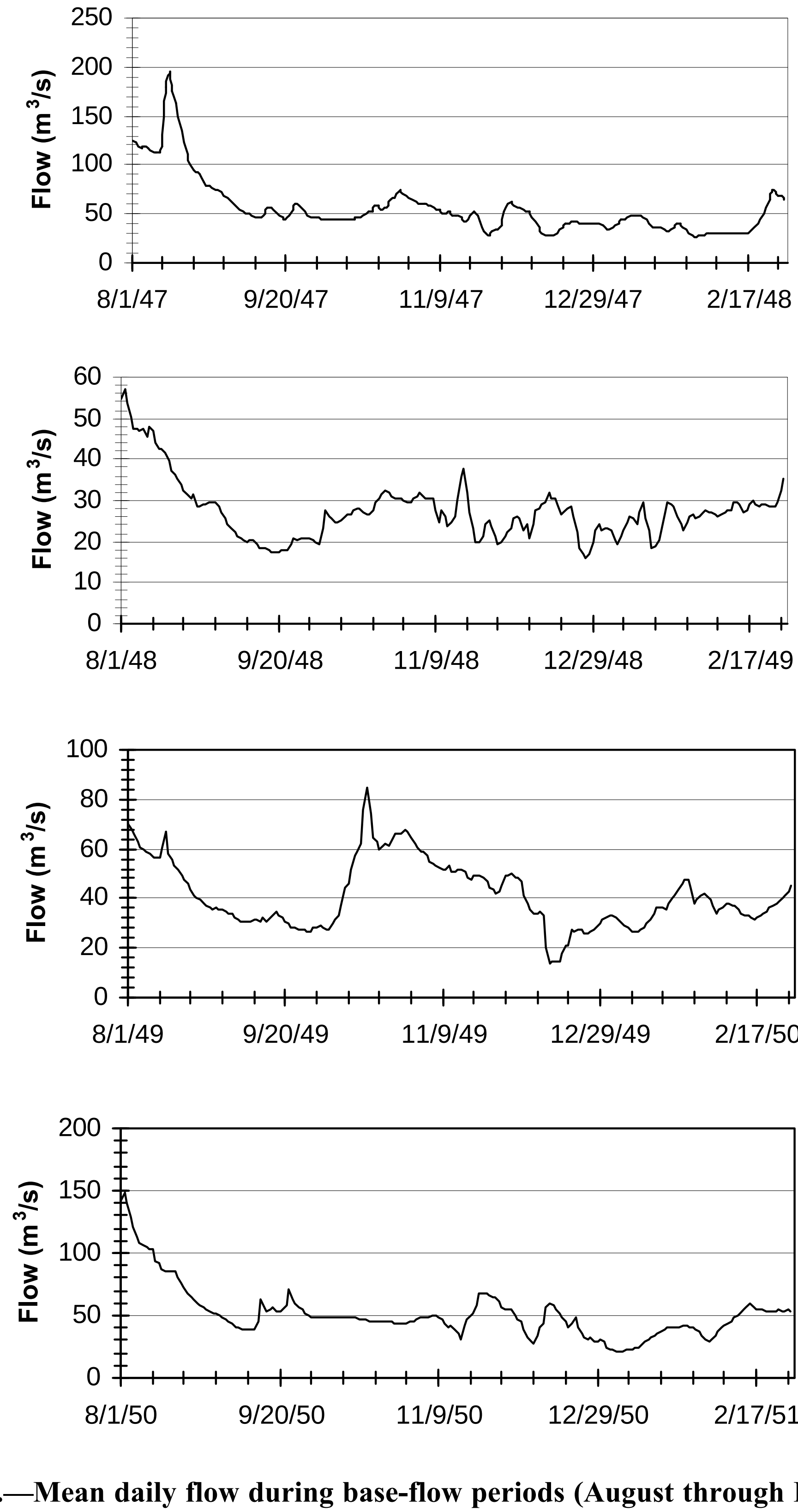
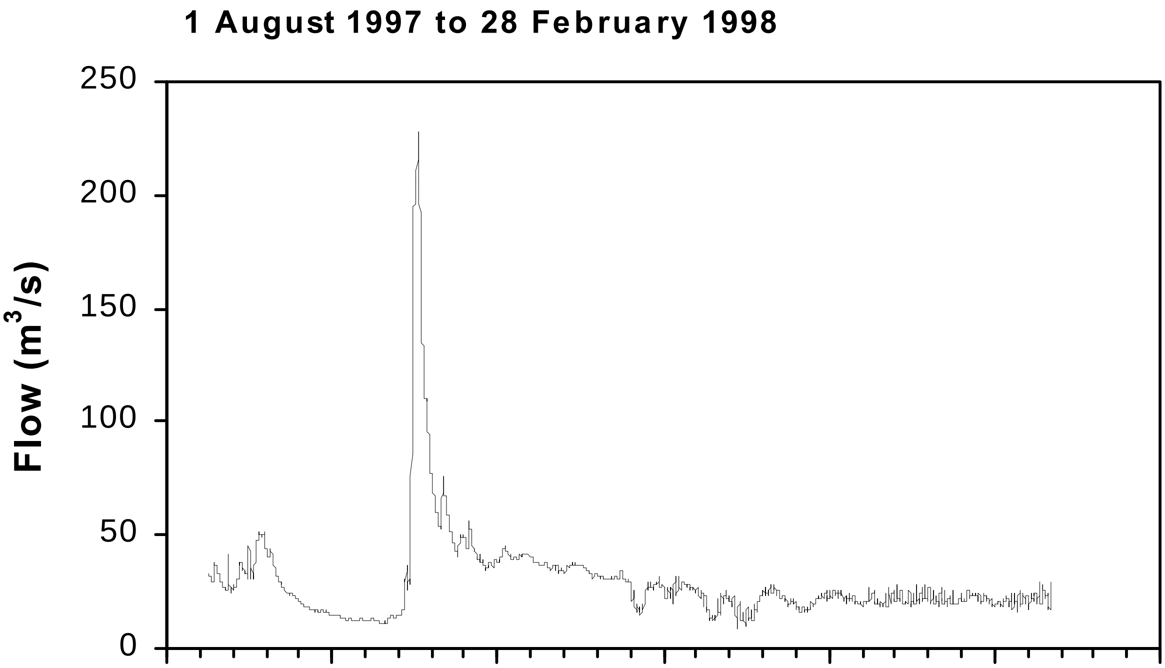


Figure 3.10.—Mean daily flow during base-flow periods (August through February) in the Green River at the USGS stream gage near Jensen, Utah, 1947–1951.



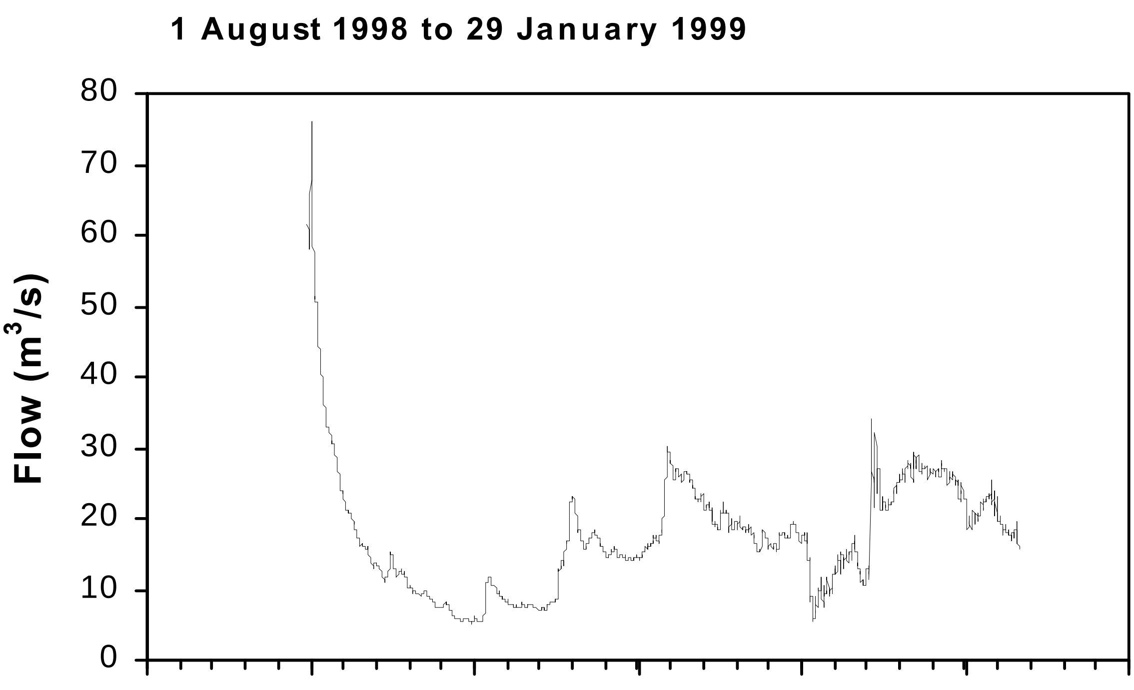


Figure 3.11.—Instantaneous flow measurements in the Yampa River as measured at the USGS stream gage at Deerlodge Park, Colorado, during 1997–1998 and 1998–1999 base-flow periods.

of record, likely no more than 5% per day or less." Derivation of this suggested 5% value was based on personal observations of flow variation in the Flathead River, Montana, rather than an evaluation of Yampa River flows. In another publication, Stanford et al. (1996) presented an evaluation that suggested that within-day variability of 5% or less was typical of the unregulated Columbia River in Washington. However, this analysis was based on an evaluation of between-day comparisons of mean daily flows averaged over a 10-year period (1920 to 1929). Such an approach is not valid for a determination of within-day flow variability.

3.4.4 Tributary Contributions to Green River Flow

Important tributaries of the Green River downstream of Flaming Gorge Dam are the Yampa, Duchesne, White, Price, and San Rafael Rivers. Figure 3.12 displays the flow contribution from each of these rivers to the Green River during 1951 through 1979. Development of the water resources within these basins affect the present-day contributions relative to the contributions shown in Figure 3.12, especially in the Duchesne River basin. Table 3.9 contains estimated data on peak flows and selected probabilities of occurrence for each of these tributary streams (Pick 1996).

The Yampa River originates along the continental divide near Steamboat Springs, Colorado. It flows in a westerly direction and joins the Green River 105 km downstream from Flaming Gorge Dam at Echo Park in Dinosaur National Monument. The Yampa River is the largest tributary of the Green River and has a great influence on Green River flow regimes; 48% of the flow in the Green River at the confluence of the Green and Yampa rivers is from the Yampa River basin.

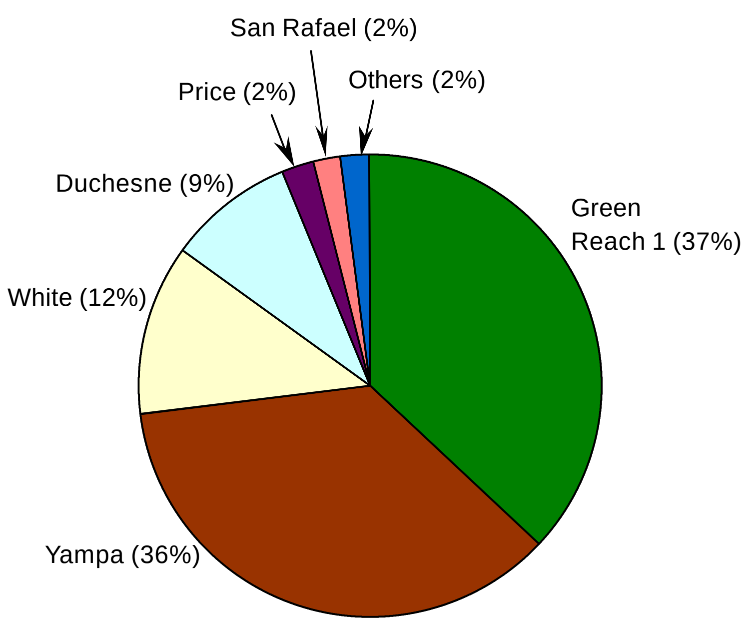


Figure 3.12.—Percent contribution of tributaries to total annual flow volume of Green River.

Table 3.9.—Peak flow estimates (m^3/s) for major tributaries of the Green River basin downstream of Flaming Gorge Dam.[a]

Recurrence Interval (Years)	Yampa River at Maybell	Little Snake River	Duchesne River[b]	White River	Price River	San Rafael River
2	286	138	108	110	116	45
5	368	207	187	153	195	68
10	419	252	232	181	246	85
25	479	314	286	215	306	105
50	521	360	320	238	345	119
100	564	411	348	261	382	140
200	603	462	374	283	416	150

[a] Periods of record for USGS stream gages are presented in Table 3.3.

[b] Peak flow estimates for the Duchesne River have not been adjusted to remove the effects of regulation, although the ability to regulate the magnitude of peak flows through reservoir operations is limited.

The Yampa River is essentially unregulated. Total reservoir-storage capacity in the Yampa River basin is only 110 million m^3, but in the Green River upstream of the Yampa River confluence, there is approximately 5,200 million m^3 of reservoir-storage capacity. Because there is limited regulation in the Yampa River basin, the river maintains a natural seasonal pattern of flow. Peak spring flows, which usually occur in late May, are high (Table 3.9), and base flows from August through February are usually low. The large flow contribution from the Yampa River, with its natural seasonal flow pattern, serves to ameliorate some of the effects of flow regulation in the Green River.

The Duchesne River basin is located entirely in Utah, and flow originates primarily from the southern Uintah Mountains. A number of south-flowing tributaries combine to form the Duchesne River, which then flows east and joins the Green River near Ouray, Utah. Unlike the Yampa River, the Duchesne River is highly regulated and greatly depleted. Numerous water-development projects alter the flow of the Duchesne River, including the Moon Lake Project, Strawberry Valley Project, Provo River Project, Uintah Indian Irrigation Project, and Central Utah Project. On the basis of estimates of irrigated acreage and consumptive-use calculations, the Duchesne River historically produced about 947 million m^3 of water annually. Federal projects and private uses of Duchesne River basin water have resulted in an average annual depletion of 676 million m^3 (USFWS 1998b).

The White River originates in the Flat Top Mountains in Colorado, flows in a westerly direction, and joins the Green River near Ouray, Utah, just downstream of the confluence of the

Green and Duchesne Rivers. Like the Yampa River, the White River is not significantly regulated. However, the yield of the White River basin is only about one third that of the Yampa River.

Both the Price and San Rafael Rivers originate in the Wasatch Plateau in the central part of Utah. Each river flows southeast to join the Green River near Green River, Utah. Although these two rivers are the largest tributaries in the 393-km area downstream of Ouray, Utah, their combined contribution is only 4% to the entire flow of the Green River.

Scofield Reservoir in the Price River basin and Joe's Valley Reservoir in the San Rafael River basin regulate the flows of these two rivers. Peak flows (Table 3.9) generally occur in late summer, either as a result of runoff from intense summer thunderstorms or releases from upstream storage.

3.4.5 Stage-Flow Relationships and the Effect of Hydropower Operations on Daily Fluctuations

Water-surface elevation (stage) is dependent on flow, but the nature of that relationship varies along the river and is strongly influenced by channel morphology. Stage-flow relationships at the Greendale, Jensen, and Green River gages are presented in Figure 3.13. This figure illustrates the differences in the relationship at these different locations and the asymptotic nature of each relationship; i.e., as flow increases, the relative incremental increase in stage lessens. Differences in channel width and floodplain characteristics at each location are reflected in the shape of the curves depicted in Figure 3.13. The river is considerably wider at the Jensen and Green River gages than at Greendale; consequently, as flow increases at Jensen and Green River, the rate of stage change is less than the rate at Greendale.

Variations in channel morphology along the river and tributary inputs serve to dampen flow and stage fluctuations that result from hydropower operations at Flaming Gorge Dam. The degree of attenuation of operations-induced fluctuations also depends on specific release parameters, including the ramp rate (the rate of change from minimum and maximum flow expressed as $m^3/s/h$), minimum and maximum flow levels, and duration of peak releases. This dampening or attenuation becomes greater at increasing distances from the dam until operations-induced fluctuations are no longer detectable.

Operations-induced fluctuations in flow and stage are thought to be important to endangered fishes because changes in these parameters can result in changes in the availability and quality of low-velocity habitats (Hlohowskyj and Hayse 1995). Fluctuations have obvious adverse effects if they are of sufficient magnitude and frequency to empty and fill important habitats on a daily basis. Adverse effects at lower fluctuation levels could result if fluctuations significantly reduced water temperatures and productivity within the habitat or caused fish to expend excess energy during winter. These effects are discussed further in Chapter 4.

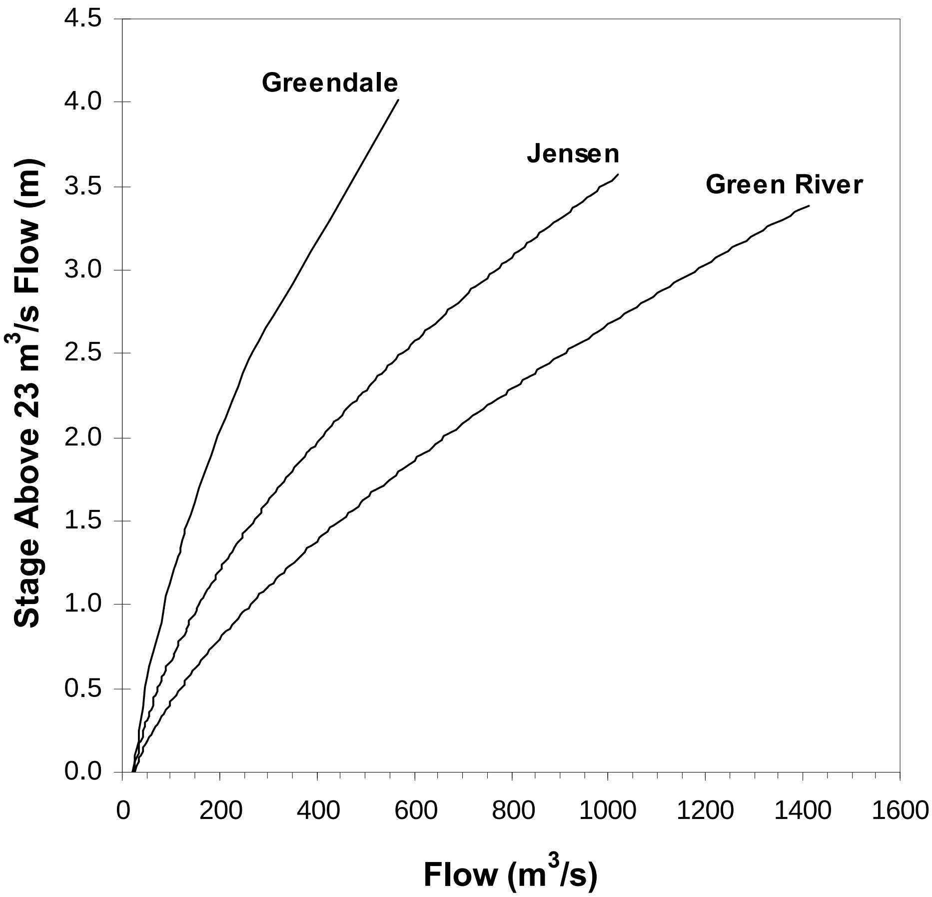


Figure 3.13.—Relationships between stage and flow in the Green River at the USGS stream gages near Greendale, Jensen, and Green River, Utah.

Yin et al. (1995) modeled changes in flow and stage that would result from several operational regimes at Flaming Gorge Dam. Immediately downstream of Flaming Gorge Dam (Greendale), maximum power-plant-capacity operations can result in daily flow changes of 107 m^3/s (varying from a minimum flow of 23 m^3/s to a maximum flow of 130 m^3/s within a 24-hour period). This same operational regime produced a daily flow change of up to 80 m^3/s (62 to 142 m^3/s) at Jensen. These flow changes produced daily stage changes of 1.5 m at Greendale and up to 0.6 m at Jensen.

Table 3.10 summarizes modeled daily flow and stage changes at Greendale and Jensen under operations complying with the 1992 Biological Opinion. During August and September (nursery period), daily changes in flow of 57 m^3/s (28 to 85 m^3/s) at Greendale produced 10 m^3/s (38 to 48 m^3/s) changes at Jensen. These daily flow changes produced stage changes of 0.9 m at Greendale and 0.1 m at Jensen.

Table 3.10.—Modeled within-day flow and stage changes for the Green River at USGS stream gages near Greendale and Jensen, Utah, under 1992 Biological Opinion operations at Flaming Gorge Dam.

	Flow at Greendale (m^3/s)			Flow at Jensen (m^3/s)		
Time Period	Daily Minimum	Daily Maximum	Within-Day Change	Daily Minimum	Daily Maximum	Within-Day Change
October	23	23	0	53	53	0
November	23	133	110	61	143	82
December	23	133	110	50	132	82
January	23	133	110	45	127	82
February	67	67	0	87	87	0
March	67	67	0	109	109	0
April	23	133	110	144	230	86
May	23	133	110	212	289	77
June 1–21	133	133	0	219	219	0
June 22–30	23	133	110	101	164	63
July 1–9	23	133	110	56	123	67
July 10–31	25	82	57	38	48	10
August	28	85	57	38	48	10
September	30	88	57	38	48	10

	Stage at Greendale (m above 23 m^3/s elevation)			Stage at Jensen (m above 23 m^3/s elevation)		
Time Period	Daily Minimum	Daily Maximum	Within-Day Change	Daily Minimum	Daily Maximum	Within-Day Change
October	0.0	0.0	0.0	0.4	0.4	0.0
November	0.0	1.5	1.5	0.4	1.0	0.6
December	0.0	1.5	1.5	0.3	1.0	0.6
January	0.0	1.5	1.5	0.3	0.9	0.7
February	0.8	0.8	0.0	0.7	0.7	0.0
March	0.8	0.8	0.0	0.8	0.8	0.0
April	0.0	1.5	1.5	1.0	1.5	0.5
May	0.0	1.5	1.5	1.4	1.8	0.3
June 1–21	1.5	1.5	0.0	1.5	1.5	0.0
June 22–30	0.0	1.5	1.5	0.8	1.2	0.4
July 1–9	0.0	1.5	1.5	0.4	0.9	0.5
July 10–31	0.1	0.9	0.9	0.2	0.3	0.1
August	0.1	1.0	0.9	0.2	0.3	0.1
September	0.2	1.0	0.8	0.2	0.3	0.1

Source: Yin et al. (1995).

Further attenuation in flow and stage occurs below Jensen, although this attenuation was not modeled by Yin et al. (1995). Table 3.11 presents available measurements of flow and stage at Jensen, Ouray, and Green River, Utah, and the release pattern of Flaming Gorge Dam during the measurement period. Only measurements taken during periods of fluctuating releases from the dam and during base-flow periods are presented. On the basis of these observations, one can conclude that significant attenuation occurs between Jensen and Ouray and that any fluctuation effects are essentially eliminated by Green River, Utah. This result is to be expected because the Green River near Ouray is wide and unconfined, with a low gradient (0.0004).

3.5 GREEN RIVER WATER TEMPERATURES

Water temperature, particularly as it relates to habitat suitability in the critical summer nursery period and to ice conditions in the winter, is an extremely important variable relating to endangered fish populations. The Service began a program of monitoring river temperatures on the Yampa and Green Rivers in 1987 (Smith 1997). Thermographs were placed at key locations on the Yampa and Green Rivers (Table 3.12). Data from these thermographs, USGS gage data, and results from work done by others are the basis for this section's description of the thermal regime of the Green River.

Winter snows accumulate in the Green River basin from October through mid-April. When air temperatures in the basin begin to rise in March and April, snowmelt and runoff begin. As flow increases, the cold water gets warmer as a result of interactions with the channel bed, the atmosphere, and direct solar radiation. Figure 3.14 compares water temperature at five locations downstream from Flaming Gorge Dam along the Green River during June through September 1996. This figure illustrates the warming that occurs downstream of Flaming Gorge Dam.

Table 3.11.—Measured within-day flow and stage changes for the Green River at USGS stream gages near Jensen, Ouray, and Green River, Utah, under different Flaming Gorge Dam operations.

	Flaming Gorge Release (m^3/s)		Stage Change (m)		
Date	**Minimum**	**Maximum**	**Jensen**	**Ouray**	**Green River**
Oct 7, 1987	23	71	not available	0.11	not available
Nov 11, 1993	23	120	0.38	not available	0.02
Nov 9, 1998	52	84	0.13	0.05	0.00
Nov 17, 1998	40	121	0.31	0.12	0.01

Table 3.12.—Location of temperature monitoring stations on the Green and Yampa Rivers.

Site	Dates of Coverage	Source
Green River at Browns Park (RK 584)	1987–1997	U.S. Fish and Wildlife Service
	1994–1995	Colorado State University
Green River at Mitten Park (RK 546)	1987–1997	U.S. Fish and Wildlife Service
Green River at Jensen, Utah (RK 479 and RK 476)	1987–1990 (RK 479), 1991–1997 (RK 476)	U.S. Fish and Wildlife Service
Green River at Ouray Refuge (RK 410)	1987–1997	U.S. Fish and Wildlife Service
Green River at Tia Juana Bottom (RK 386)	1987–1988	U.S. Fish and Wildlife Service
Green River at Green River, Utah (RK 189)	1987–1995	U.S. Fish and Wildlife Service
Yampa River at Echo Park	1987–1997	U.S. Fish and Wildlife Service

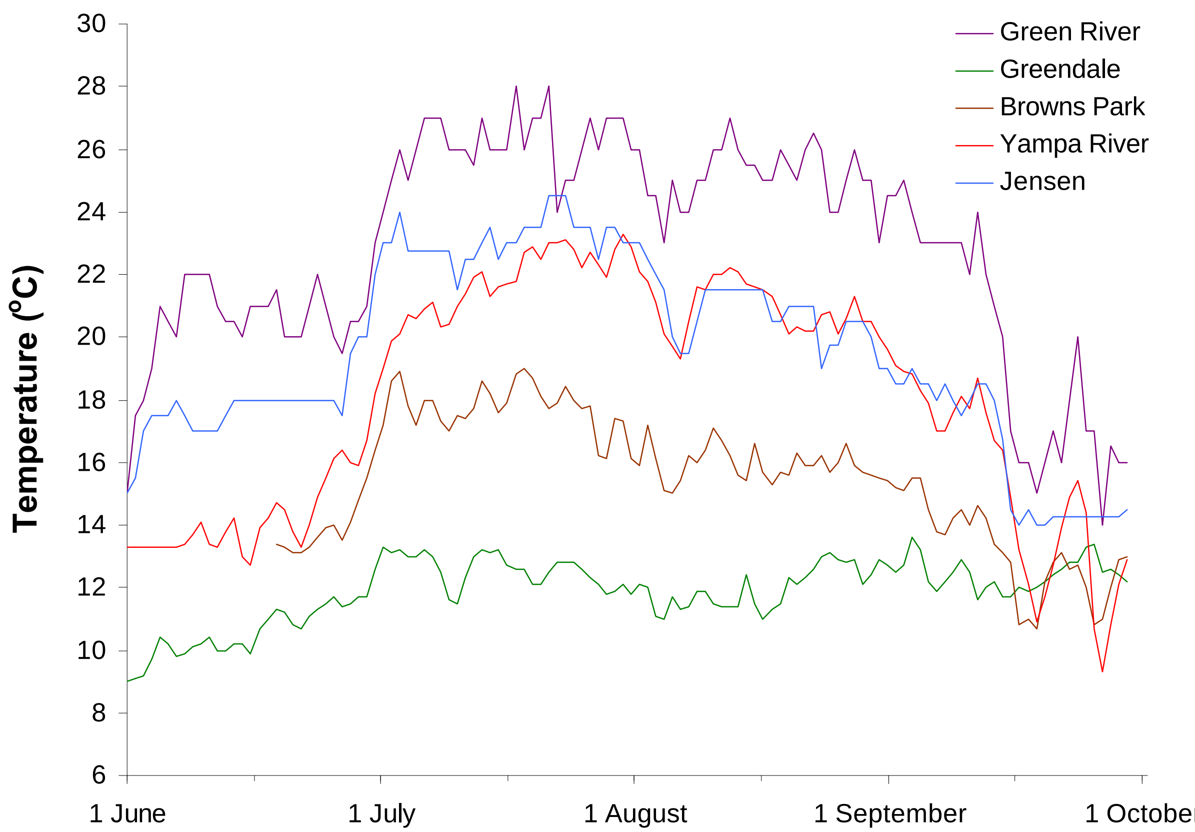


Figure 3.14.—Green River water temperatures at five locations during base flow in 1996.

3.5.1 Summer Water Temperatures

Summer water temperature is important to the endangered fishes because temperature affects the productivity of the aquatic food base, growth and survival of larval fish, and conditioning of adult fish. Summer water temperature is largely a function of specific weather conditions during a particular summer, but is also strongly influenced by the volume and temperature of releases from Flaming Gorge Dam during this period. Water temperature is discussed for each of the three reaches in the following sections.

As a general rule, in water years with more water, the water temperatures remain colder into summer. Water years in which snowmelt and runoff occur early (such as in water year 1962, when the peak flow occurred from mid-April to mid-May) are exceptions to this rule. During water year 1995, which had a high volume of water with a long peak-flow duration, water temperatures stayed low well into July. During water years with less water, water temperatures get warmer earlier in the season because base flows are low and reached earlier in the year (Section 3.4.3).

3.5.1.1 Water Temperature in Reach 1

The dominant factor influencing water temperature in Reach 1 is the temperature of water released from Flaming Gorge Dam. Release temperature is adjusted through the use of a selective withdrawal structure. This structure, which withdraws water from different positions in the Flaming Gorge Reservoir water column, was installed in 1978 to allow control of water temperatures for trout. During typical winter operations, water is drawn from deep within the reservoir through a fixed gate at an elevation of 1,789 m and a second mobile gate at 1,802 m. Water at these levels is 4ºC and is the warmest available at this time of year. During spring (usually early April), the mobile gate is moved within about 12 m of the surface to draw the warmest water available. Reservoir operators adjust the withdrawal system to find a layer of water with a temperature of 13ºC throughout the summer, so that a constant temperature of release water is maintained until mid-October when the temperature of the release is lowered. The gate maintains a minimum 12-m distance between the surface and the intake to reduce the possibility of a vortex and entrainment of air and debris. Usually by mid-July, gates are at an elevation of 15 m or more below the reservoir surface.

With this operation, suitable temperatures for trout extend to upper Browns Park. As the river flows through Browns Park, it widens, and its water temperature increases. From Browns Park, the river enters Lodore Canyon, which has a north-south orientation that limits exposure to direct solar radiation. Water temperature in Lodore Canyon to the confluence with the Yampa River typically increases about 2ºC as the rock mass of the canyon radiates heat to the air and water.

Effects of release patterns from Flaming Gorge Dam on the thermal regime of the Green River in Reach 1 were described by Bestgen and Crist (2000). They developed empirical regression models that predicted water temperature in the reach over a range of discharges and in different seasons. Air and water temperature data were used to develop models for upper Browns Park

(RK 418), lower Browns Park (RK 392.8), and lower Lodore Canyon (RK 363.2). It was assumed that water released from the dam was a constant 13°C, consistent with present operations.

Water temperature of the Green River downstream of Flaming Gorge Dam was best predicted as a function of flow and ambient air temperature (Bestgen and Crist 2000). Ambient air temperature had a large positive effect on water temperature; flow had a smaller and inversely proportional effect. The influence of ambient air temperature increased in importance in a downstream direction. Because ambient air temperature has such a large effect, annual variations in regional weather patterns may play an important role in determining the thermal regime of the Green River downstream of Flaming Gorge Dam. However, even though flow has less effect on water temperature, it can be manipulated through modification of release patterns.

3.5.1.2 Water Temperature in Reach 2

Thermal mixing at the confluence of the Green and Yampa Rivers is seasonally dynamic and has an important effect on Green River water temperatures. During winter, water released from Flaming Gorge Dam is warmer than the Yampa River. Although the Yampa River begins to get warmer in spring, temperature in the Green River remains low and stable as a result of cool Flaming Gorge Dam releases. From the beginning of spring runoff through mid-summer, the temperature of the Green River downstream of the confluence is strongly influenced by the temperature of water flowing from the Yampa River. During late summer, the situation reverses as the temperature is controlled by the cooler, higher-volume releases from Flaming Gorge Dam.

From the Yampa River confluence, the Green River flows west into Whirlpool Canyon and then into Island and Rainbow Parks. Water temperature in Island and Rainbow Parks increases because the river slows down and spreads out, exposing the water to a large channel and radiant solar energy. From Rainbow Park, the river drops into Split Mountain Canyon, where it is shaded by canyon walls and where its water velocity increases. Consequently, the water temperature changes little through this canyon.

The Green River enters the Uinta Basin near Jensen, Utah. Through this broad alluvial area, the river spreads out into a wide meandering channel, and, during summer, its water temperature increases further (Figure 3.14).

3.5.1.3 Water Temperature in Reach 3

The Duchesne and White Rivers join the Green River near Ouray, Utah, but do not appreciably change the temperature of the Green River. Several kilometers downstream from the confluence of the Green River with the White and Duchesne Rivers, the Green River enters Desolation and Gray Canyons, where diel fluctuations in water temperature are moderated by warmth from the canyon walls radiating to the air and water at night. Downstream from these canyons, the Price River joins the Green River but does little to affect water temperatures of the Green River.

Downstream from its confluence with the Price River, the Green River enters a second large alluvial plain, where the city of Green River, Utah, is located. The river channel widens in this area, water velocity decreases, and water temperature increases slightly (Figure 3.14). The Green River continues southward from Green River, Utah; is joined by the San Rafael River; enters Stillwater Canyon; and then flows into the Colorado River. In this section, the increase in solar radiation is significant; day and night temperatures are higher and the river is warmer here than upstream. This increase is especially noticeable in the canyon area, where massive rock structures get warm during the day and reflect heat back to the air and water at night. This process moderates diel-temperature variation as the river meanders through the canyon.

3.5.2 Ice Conditions

The formation of river ice covers reflects the meteorologic and hydrologic conditions of the region through which the river flows and the hydraulic conditions of the river channel itself. The water temperature represents the balance of heat transfer into and out of the river. Ice-cover formation is initiated when frazil ice forms in high-gradient portions of the river. Frazil ice is small crystals of ice that form when air that is colder than the freezing point of water supercools (i.e., reduces temperature to slightly below the freezing point) the surface layer of water, typically in turbulent sections (e.g., rapids) of the river. The frazil ice is transported downstream, until it reaches low-velocity areas, where it consolidates into a solid ice cover. The ice cover then builds in an upstream direction from this point as additional ice floes (floating masses of consolidated frazil ice) are transported by the current. The upstream point to which the ice cover will progress depends on the continued formation of frazil ice as a result of sub-zero air temperatures and the velocity of flows at the upstream edge of the ice cover. As the flow velocity increases, there is a greater tendency for ice floes arriving at the upstream end of the ice cover to be pushed underneath the ice cover and transported downstream. For additional information about ice formation, refer to Hayse et al. (2000).

Breakup transforms an ice-covered river into an open river. Two types of breakup bracket those commonly found throughout most of North America. At one extreme is thermal meltout. During thermal meltout, the ice cover deteriorates as a result of warming and the absorption of solar radiation, and it melts in place, with no increase in flow and little or no ice movement. At the other extreme is the more complex and less understood mechanical breakup. Mechanical breakup requires no deterioration of the ice cover and results from an increase in flow entering the river. The increase in flow induces stresses in the ice cover, and these stresses, in turn, cause cracks and the ultimate fragmentation of the ice cover into pieces that are transported by the channel flow. Most river-ice breakups (including those in the Green River) actually fall somewhere between the extremes of thermal meltout and mechanical breakup, because the breakup usually occurs during warming periods, when the ice-cover strength deteriorates to some degree and the flow entering the river increases as a result of snowmelt or precipitation.

Valdez and Masslich (1989) observed increased movement of adult endangered fishes in portions of Reach 2 during periods of ice breakup in the Green River. They hypothesized that the increased movement could affect the overwinter survival of the fish. Although the degree to which operations of Flaming Gorge Dam caused breakup and movement of ice in the Green River was unclear at the time, the 1992 Biological Opinion (USFWS 1992) recommended stable flows between ice formation and breakup. The reasonable and prudent alternative of the Biological Opinion called for additional studies to evaluate effects of fluctuating flows on conditions in overwintering areas for the endangered fishes.

Prior to construction of Flaming Gorge Dam, surface ice probably formed in Reach 1 beginning in December and persisted to at least early March, in a pattern similar to that of the Yampa River. Occasionally, mid-winter rainfall or warm periods may have led to ice breakup, but ice breakup was probably rare during winter. Since construction of Flaming Gorge Dam, water temperatures immediately downstream of the dam are higher during winter because of hypolimnetic releases of warmer water (approximately 4°C) from the dam, and main channel portions of Reach 1 typically remain ice-free throughout the winter.

During periods when the air temperature is colder than the water temperature, the river water cools as it travels downstream. During very cold winters, the reported upstream extent of ice cover on the Green River is in the vicinity of Island and Rainbow Parks, although shoreline ice may occur farther upstream than this. During less severe winters, the upstream extent of ice cover is in the vicinity of the USGS gage near Jensen, Utah. The presence of ice cover has been observed at this location in all years for which reliable observations were made (Valdez 1995; Hayse et al. 2000).

Valdez and Cowdell (1999) investigated the formation of ice and conditions in backwater areas of Reach 2 under different operational regimes at Flaming Gorge Dam. Although their study was confounded by mild conditions that occurred during the winters of 1993–1994 (i.e., high-volume, high-fluctuation regime) and 1994–1995 (i.e., low-volume, low-fluctuation regime), results suggested that ice processes in backwaters were largely independent of dam operations. Some frazil ice accumulated in the backwaters, but all of the backwaters studied maintained areas of open water greater than 30 m^2 and greater than 9 cm deep. The measured concentration of dissolved oxygen under the backwater ice covers was always greater than 5 mg/L.

Hayse et al. (2000) investigated the effects of fluctuating flows on main-channel ice processes in the Green River between the downstream end of Split Mountain (RK 515) and the Ouray, Utah, bridge (RK 399). The overall goal of that study was to assess the influence of the daily release schedule of Flaming Gorge Dam on river-ice processes in the study reach, which is known to be used by overwintering endangered fishes (Valdez and Masslich 1989). Analysis of historic measurements of water and air temperature and ice observations demonstrated that the temperature of water entering the study reach near the Jensen gage and just upstream of the Chew Bridge was often 0°C during winter and that daily average air temperatures were consistently below 0°C during December, January, and most of February. Ice cover was observed in the study reach during every winter for which reliable records were available. Historic observations indicate that the formation of ice cover in the study reach appears to follow a consistent pattern each winter. The daily release schedule of Flaming Gorge Dam, whether steady or fluctuating as a result of hydropower demand, did not appear to affect the basic outline of that pattern.

During a field study in 1997, Hayse et al. (2000) compared conditions of ice cover between the downstream end of Split Mountain Canyon and the Ouray Bridge under steady flows of 69 m^3/s at the Jensen gage and under fluctuating flows ranging from 48 m^3/s to 99 m^3/s within a single day. Stage changes measured in Reach 2 during these fluctuations in flow ranged from 24 cm at the Jensen Bridge to 6 cm at the Ouray Bridge, while a stage change of approximately 37 cm was reported at the Jensen gage for this period. At the initiation of fluctuating flows, the upstream extent of ice cover in the Green River was at RK 508.9 and had an average thickness of 21.5 cm. After several days of fluctuating flows, the upper 8 km of the ice cover broke up, but the thickness of ice in the remaining portion of the study reach did not change significantly. On the basis of field studies and an ice-process model developed for the study reach, Hayse et al. (2000) concluded that daily fluctuations within the range of hydropower operations that occurred during the winter of 1997 (22.7 to 85.0 m^3/s from Flaming Gorge Dam and 48 to 99 m^3/s at the Jensen gage) are unlikely to significantly affect the formation or breakup of ice covers of a comparable thickness downstream of RK 483. The results indicated that the fluctuations would have a more pronounced effect and could affect the formation and breakup of ice cover upstream of that point.

Frazil ice deposits several feet thick were observed throughout an 18-km segment (RK 485 to RK 503) during the winter of 1987–1988 when releases from Flaming Gorge Dam ranged from 37 to 67 m^3/s (Valdez and Masslich 1989). The principal difference in conditions between the two winters was that air temperatures during the winter of 1987–1988 were considerably colder, contributing to the heavy production of frazil ice in areas upstream of the stationary ice cover. It is likely that large fluctuations in flow during periods with heavy frazil ice production contributed to the transport and deposition of frazil ice under the upstream portion of the stationary ice cover. On the basis of ice-process modeling and field observations, Hayse et al. (2000) concluded that the deposition of frazil ice downstream of the Jensen gage would be unlikely to extend farther than approximately 16 km from the upstream edge of the ice cover during most winters.

3.6 GEOMORPHIC PROCESSES IN THE GREEN RIVER

Physical attributes of the Green River and its valley affect the geomorphic consequences of Flaming Gorge Dam release patterns and other characteristics of flow. Recent research on the Green River has focused on relationships between sediment transport and channel morphology over a range of flows in different geomorphic settings. Research summarized in this section and described in abstracts in Appendix B was conducted to provide a basis for refinement of operations at Flaming Gorge Dam by describing details of channel morphology, hydraulics, and sediment transport that are important considerations in describing habitats of the endangered fishes. This section is organized according to geomorphic characteristics (channel planforms) and in-channel and floodplain processes.

3.6.1 Channel Planforms

As described in Section 3.3, the Green River downstream of Flaming Gorge Dam consists of a series of linked segments of three channel planform types without a systematic downstream change from one planform to the next. The channel planforms types are restricted meanders, fixed meanders, and canyons with abundant debris fans (Figure 3.15). These planforms are described below because the geomorphic processes and habitat conditions within each type can be quite different.

3.6.1.1 Restricted and Fixed Meanders

Restricted meanders occur in broad alluvial terraces that are bounded by relatively more resistant geology (Figure 3.15). Valleys in which restricted meanders occur are relatively wide (greater than 1.5 km), and only the outside bends are in contact with bedrock. Restricted meanders occur in Reach 1 (Browns Park) and much of Reach 2.

Fixed meanders are confined by resistant geology on both outside and inside bends and result from symmetrical incision associated with rapid down-cutting through the geologic formation (Figure 3.15). Labyrinth Canyon in Reach 3 is characterized by fixed meanders.

Typical elements of fixed and restricted meanders include the channel, vegetated islands, unvegetated bank-attached compound bars, unvegetated island-attached compound bars, and unvegetated mid-channel compound bars. Permanent islands are less common in fixed meanders than in restricted meanders. In-channel deposits are typically sand, although gravel bars sometimes occur. Typically, bank-attached compound bars occur on alternating sides of the river. Shoreward from these bars is the vegetated floodplain at the edge of the "bankfull" channel (i.e., the channel that can accommodate stream flow without overtopping the banks), and streamward from the bars is the meandering thalweg. Island-attached compound bars are bounded by vegetated islands and the thalweg.

> ***Channel planform*** – The configuration of a stream as seen from above. Three channel planforms, defined below, are found along the Green River downstream of Flaming Gorge Dam and are shown in Figure 3.15.
>
> ***Restricted meander*** – Sinuous portion of river that flows through broad alluvial terraces bounded by relatively more resistant geology. Only the outside bends are in contact with bedrock.
>
> ***Fixed meander*** **–** Sinuous portion of river that is confined by resistant geology on both outside and inside bends.
>
> ***Canyons with abundant debris fans*** – Relatively straight sections of the river confined on both sides by resistant geology with coarse sediment deposits (debris fans) at the mouths of tributaries.

At low discharge, exposed compound bars have an irregular topography caused by chute channels that dissect the bar platform. Chute channels are oriented in a downstream direction, crossing from the streamward to shoreward side at the upstream end of the bar and from the

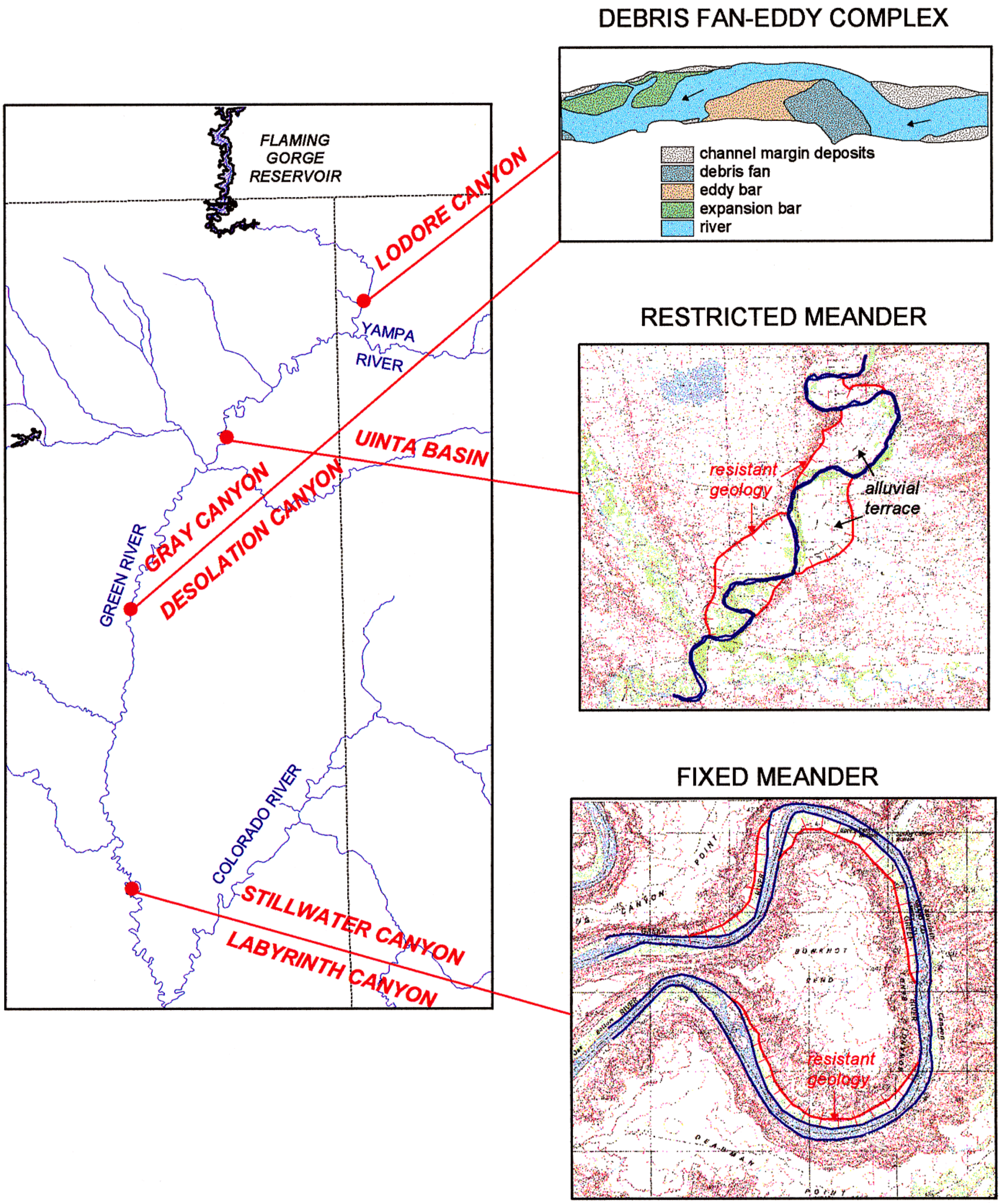


Figure 3.15.—Channel planform types in the Green River downstream of Flaming Gorge Dam.

shoreward to streamward side at the downstream end of the bar. The topography of a bar is more complex where there are more chute channels. At some sites and in some years, secondary bars become attached to the shoreward margins of these compound bars. At the downstream end of most compound bars, chute channels may converge into one persistent and deep secondary channel that separates the downstream end of the compound bar from the floodplain. The remainder of the bars are composed of broad, level platforms and linear ridges that may be partly vegetated.

As flow recedes from the annual peak discharge, higher-elevation parts of the bar platform are exposed and small areas of separated flow develop in the lee of these islands. At these discharges, chute channels actively transport sediment. Upon further recession of flow, chute channels at the upstream end of the compound bar become exposed, and flow in the secondary channel ceases. Thereafter, the secondary channel becomes an area of mostly stagnant water. These low-velocity areas (backwaters) provide important nursery habitats for larval fish, especially the Colorado pikeminnow (Section 4.2).

3.6.1.2 Canyon Reaches with Abundant Debris Fans

Canyons consist of relatively straight sections of river with resistant geology on both sides of the river. Debris fans are areas of coarse sediment deposits at the mouths of tributaries; these sediments are delivered to the main channel during high-flow events in tributaries. In canyons, debris fans form a sequence of conditions including: (1) a slack-water area upstream from the debris fan, (2) a channel constriction at the debris fan, (3) an eddy or eddies and associated bars in the expansion area downstream from the fan, and (4) a downstream gravel bar (Figure 3.15; Schmidt and Rubin 1995). These “debris fan-eddy complexes” exist at the mouths of nearly all debris-flow-generating tributaries. Downstream of Flaming Gorge Dam, canyons with abundant debris fans include Lodore Canyon (Reach 1), Whirlpool and Split Mountain Canyons (Reach 2), and Gray and Desolation Canyons (Reach 3).

Longitudinal profile, channel geometry, and the occurrence of rapids within canyons are strongly influenced by tributary-fan frequency. The bankfull channel width-to-depth ratio is smaller and the gradient is steepest in reaches with the highest fan frequency; all rapids are caused by debris fans or the gravel bars below debris fans that are composed of reworked debris-fan material. Expansion gravel bars are the other element of coarse-grained alluvial deposits in debris-fan dominated canyons. These bars are located in the flow-expansion zone downstream from debris-fan eddies where wider channel conditions resume (Grams and Schmidt 1999).

Debris fans in Desolation Canyon (Reach 3) are large and at low elevation. Only the small active portion of the fan delivers sediment that restricts flow and causes rapids and eddies in the modern channel, whereas the main portion of the debris fan is so large that it acts more like a meander bend as the river flows around the fan (Orchard and Schmidt 2000).

3.6.2 Sediment Dynamics, Shoreline Complexity, and Low-Velocity Habitats

Within a particular reach, shoreline complexity is affected by sediment-deposition processes and geologic conditions. Consequently, shoreline complexity varies considerably among different planform types. An understanding of shoreline complexity is important because it affects the distribution and suitability of habitats, including backwaters and other low-velocity habitats used as nursery areas by the endangered fishes, especially Colorado pikeminnow and humpback chub.

Direct measurements of shoreline complexity calculated from topographic maps of compound bars in different study reaches show that complexity is greatest at those discharges when the bar surface is partly inundated and where chute channels are inactive. At a very low river stage, complexity is determined by the topography of the bar margins, which are typically simpler in shape than are the upper-bar surfaces. When higher discharges inundate the bar surface, complexity is determined by the planform of the floodplain edge. Olsson and Schmidt (1993) showed that the elevation of greatest shoreline complexity changes from year to year because the elevation and topographic complexity of bars change depending on the hydrologic regime during spring runoff.

The longitudinal distribution of channel planforms (Section 3.6.1) for the Green River affects the longitudinal distribution of shoreline complexity, and the locations of high or low complexity change with discharge. Restricted meanders have considerable shoreline complexity at bankfull discharge because of the presence of vegetated mid-channel islands. In contrast, fixed meanders have relatively little available habitat at bankfull discharge because the banks are relatively smooth and there are few permanent mid-channel islands. At intermediate stages, complexity increases dramatically, and some segments have significantly more complexity than other segments. At a very low stage, there is little difference in habitat complexity between fixed and restricted meanders, but these segments have higher habitat complexity than canyons (Schmidt 1996).

Except at very low flow, shoreline-complexity indices can be relatively high in canyons with abundant debris fans. In contrast to alluvial reaches, whose banks typically have smooth transitions from one orientation to another, debris-fan segments have banks that are composed of coarse, angular deposits where bank orientations have sharp angles. These divergences give rise to low-velocity habitats even at high river stage.

Shoreline complexity – A geomorphic variable that describes the degree that shorelines deviate from a straight line, calculated by dividing the total length of both shorelines by the mid-line of the channel.

Low-velocity habitat – An area within the river channel that has lower flow velocity than the main channel of the river. These areas provide refuge for fish and allow them to conserve energy and are particularly important for larval and young-of-the-year fish. Portions of the river with complex shorelines generally have more low-velocity habitat.

Backwater – A generally shallow area within the river channel with little or no flow that is situated downstream of an obstruction, such as a sand or gravel bar, and that has some direct surface water connection with the river.

Eddy – An area downstream of an obstruction within the river channel where the local current moves against the main current in a circular motion.

An important component of shoreline complexity is backwater habitat; this comprises areas of low or no flow velocity that serve as important nursery habitats for young fishes (Chapter 4). After the 1987 spring peak, remote sensing was used to examine trends in the size, total area, and numbers of backwaters over a range of flows (Pucherelli et al. 1990); the total area of backwater habitat in Reach 2 was maximized at flows between 37 and 55 m^3/s (Figure 3.16). The relationship to flow at the two study areas within Reach 3 was less clear, but the gage data used to determine this relationship probably did not accurately reflect actual flow at the study areas.

Bell (undated) used aerial photography to measure the amount of backwater present at Jensen and Ouray in Reach 2 in October 1993 and August 1996 and at Mineral Bottom in Reach 3 in October 1993 and August 1996. Flows on these dates were similar (46 and 48 m^3/s, respectively, at the Jensen gage and 57 and 63 m^3/s, respectively, at the Green River gage). For comparison, Bell (undated) presented the amount of backwater area in 1987 as determined by Pucherelli et al. (1990) at comparable flows (46 m^3/s at the Jensen gage, 79 m^3/s at the Green River gage). Despite the similarity in flows at the time of photography, the area of backwater habitat differed considerably among years (Figure 3.17). Bell postulated that differences in annual peak flows could have produced the observed differences.

Rakowski and Schmidt (1999) concluded that establishing a single target flow that is intended to maximize habitat availability every year is inappropriate because bar topography, and therefore habitat availability, changes annually in response to the passage of peak flows. They placed the magnitude of flood peaks into three categories: (1) very low peaks that do not inundate the bar tops but rearrange sediment along the bar margins, (2) low peaks that inundate the bars but do not overtop the banks, and (3) large floods that overtop the banks. Although the channel responds rapidly to changes in discharge, the imprint of antecedent conditions on the low-flow channel form (for example, the relative elevation of the bar tops and the distribution of sediment within the channel) survives flood passage, especially the passage of low-magnitude floods. Thus, the availability of nursery habitat for the endangered fishes during low-flow periods depends on the channel form that has resulted from recent floods and antecedent channel conditions (Table 3.13; Rakowski and Schmidt 1999).

Detailed measurements of a sand bar in 1993 and 1994 were used to determine the inter-annual changes that occur to habitat availability as a result of flood passage in Reach 2 (Rakowski and Schmidt 1999). Spring runoff was much higher in 1993 (566 m^3/s) than in 1994 (331 m^3/s), and the topography of the study bar during low flows as well as the configuration and availability of nursery habitats differed between those years (Rakowski and Schmidt 1999). During both years, habitat availability was maximized at flows much greater than the target flows identified in the 1992 Biological Opinion. In 1993, the amount of nursery habitat was highest at flows of about 140 m^3/s; in 1994, the greatest amount of habitat was available at 120 m^3/s. The difference between the two years in the relationship between flow and habitat availability was so great that the flow that produced the maximum amount of habitat in 1993 produced no habitat in 1994.

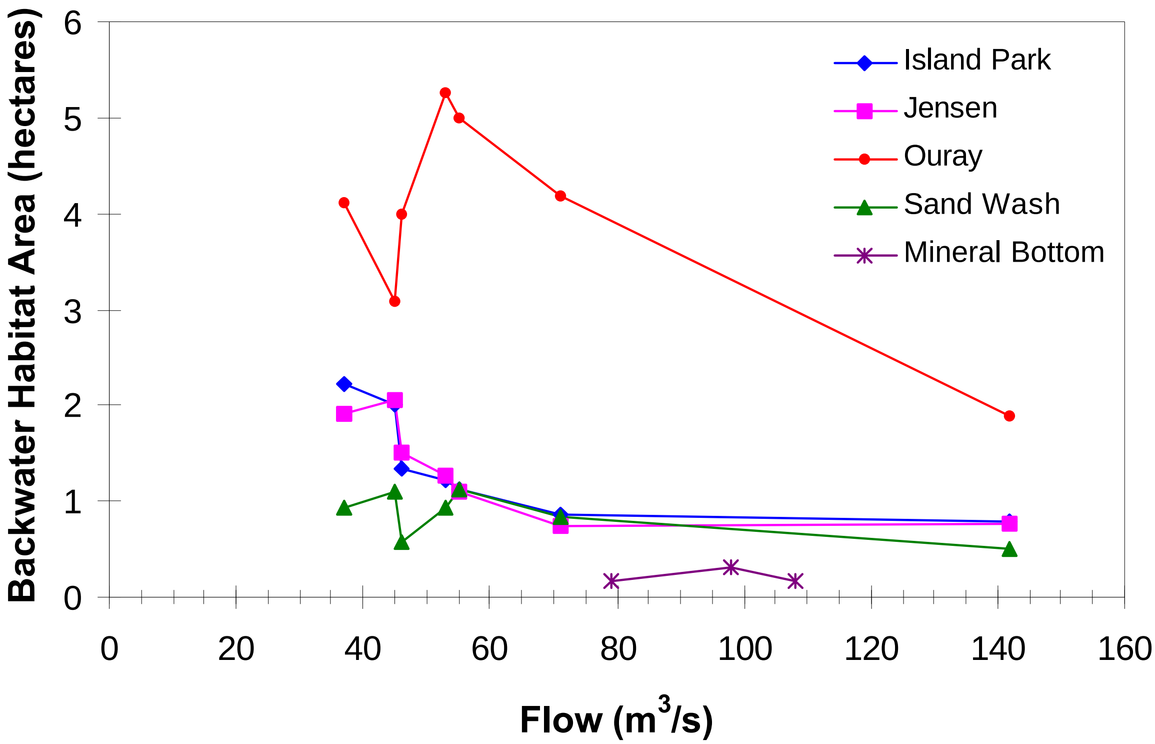


Figure 3.16.—Relationship between backwater habitat area and flow at selected sites in Reaches 2 and 3 of the Green River in 1987. Source: Pucherelli et al. (1990)

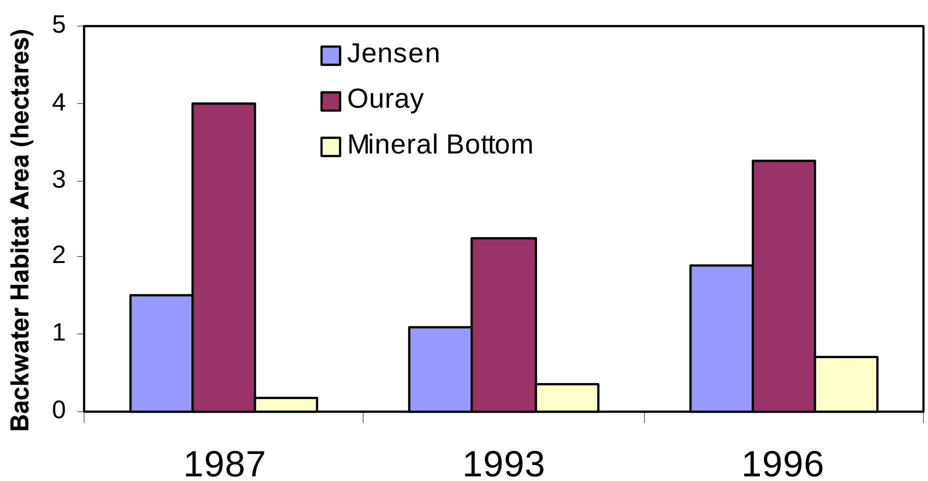


Figure 3.17.—Amount of backwater habitat available in 1987, 1993, and 1996 at Jensen, Ouray, and Mineral Bottom on the Green River. (Backwater habitat area was determined from aerial photographs taken at approximately the same flow each year.) Source: Bell (undated)

Table 3.13.—In-channel response of sandbars to various flood levels in the Green River.[a]

Elevation of Existing Bar Tops	Effect of Flood Magnitude on In-Channel Habitats		
	Less Than Bar-Top Flood	**Less Than Bankfull**	**Greater Than Bankfull**
Low	Rearranges habitats. Net change in habitat availability unknown.	Maintains the increased availability of deep habitats. Maintains or decreases availability of shallow habitats.	**Increases availability of deep habitats. Decreases availability of shallow habitats. (1993 runoff peak)**
High	**Increases shallow habitat availability. Decreases deep habitat availability. (1994 runoff peak)**	*Rearranges habitats. Net change in habitat availability unknown.*	*Maintains the increased availability of deep habitats. Maintains or decreases availability of shallow habitats.*

[a] Effects in boldface were measured; those in italics were modeled. Unmodeled and unmeasured predictions are shown in normal typeface. Source: Rakowski and Schmidt (1999).

The larger flood peak of 1993 increased the height and range of the elevations of the nursery habitat's bed, thus increasing the flow at which habitat availability was maximized and broadening the range of flows at which habitat was available (Rakowski and Schmidt 1999). The lower flood peak of 1994 decreased the range of bed elevations by scouring the higher elevations and filling the lower elevations, thus narrowing the range of flows at which habitat was available and shifting the peak of habitat availability to a lower elevation and flow. A series of low-peak floods would continue this process until the discharge that maximized habitat availability was quite low. In 1992, after six years of drought, habitat availability was maximized at 35 m^3/s (Rakowski and Schmidt 1999).

Eddies are another important component of low-velocity habitat in the Green River, but these habitats form behind geomorphic features (e.g., debris fans, large rocks) that are more resistant than sediment bars to annual peak flows. In Desolation and Gray Canyons, increases in flow change the distribution and type of eddy habitat present, but the total area of eddy habitat changes little (Orchard and Schmidt 2000). At any given flow, approximately 25% of the shorelines occur within eddies. At base flow, small frequent shoreline eddies make up most of the eddy habitat and increase in frequency between 59 and 198 m^3/s. As flow increases from 198 to 765 m^3/s, large, infrequent eddies formed by constrictions in the channel make up the majority of eddy habitat.

Although the availability of low-velocity shoreline habitat apparently changes little in Desolation and Gray Canyons with changes in flow, habitat conditions as determined by substrate characteristics in those habitats may change considerably (Orchard and Schmidt 2000). Low flows produce highly complex shoreline habitats with mostly bare sand and gravel substrates. Higher flows submerge these bars and substantially increase the amount of inundated vegetation along shorelines. The amount of talus shorelines in eddies peaked near 198 m^3/s and declined at higher flows.

Flooded side canyons also provide low-velocity habitats used by fish; the relationship between the area of flooded side-canyon habitat and flow in Reach 3 was examined by FLO Engineering, Inc. (1996). Flooding of side canyons begins at a discharge of approximately 198 m^3/s. At flows greater than 198 m^3/s, a linear increase in the area of flooded side-canyon habitat occurs until bankfull discharge (1,104 m^3/s) is reached; only 2 ha of flooded side-canyon area is available at this study site at bankfull discharge. There is no optimum flow for the area of inundation of side-canyon habitat; a higher discharge results in a larger amount of flooded area.

3.6.3 Sediment Dynamics and Spawning Substrates

Cobble and gravel deposits free of silt and sand are preferred spawning areas of the endangered fishes (Chapter 4), and the suitability of these areas for spawning are affected by sediment-transport and depositional patterns. The morphologic characteristics and sediment-transport regime at a known spawning site for razorback suckers were described by Wick (1997). This spawning site on the Green River is in Reach 2 upstream of Jensen, Utah, about 156 km downstream from Flaming Gorge Dam. It was studied between 1992 and 1996. Sediment-deposition and scour patterns were described by using mathematical models of hydraulics and sediment transport calibrated to observed field data. This modeling indicated that a downstream constriction in the river created a "backwater effect" at discharges above 340 m^3/s and resulted in sediment deposition on portions of the bar. Measured sedimentation of the bar began at flows of 200 m^3/s, and flows resulted in deposition of about 0.6 m of sand as they approached 650 m^3/s (Wick 1997). At lower flows, the backwater effect did not occur, the channel became narrower, and higher velocities scoured sand from the bar, making it suitable for spawning.

The timing of peak flow was found to be important in maintaining this spawning bar. Wick (1997) suggested that the magnitude and timing of releases from Flaming Gorge Dam could affect the suitability of the bar and could be manipulated to ensure that the bar substrate is clean.

Harvey and Mussetter (1994) reported on the hydraulics at a potential spawning area for Colorado pikeminnow located at the head of Gray Canyon in Reach 3. They used field data from this site to test a proposed physical process-biological response model for spawning-habitat formation. This model was initially developed from data and analyses conducted about 27 km upstream from the Yampa and Green River confluence in lower Yampa Canyon (Harvey et al. 1993). The model indicated that high discharges are responsible for the construction of the spawning bar but not for the actual formation of the spawning habitat. Downstream hydraulic controls cause a backwater condition that results in the formation of the bar as a heterogenous mass of sediments is deposited during high flows. Reduced tailwater during recessional flows causes a steepening of the local hydraulic gradient, which in turn leads to bar dissection and erosion of chute channels. Dissection of the bar causes the fines to be flushed, and this process is enhanced by reduced sediment delivery from upstream due to deposition in the upstream pool. A clean cobble substrate, at incipient motion and suitable for egg adhesion, is found within the chute channels.

The downstream hydraulic control for this bar is formed by two coarse-grained and horizontally opposed alluvial fans that have prograded into the channel to form a constriction in the flow path. Hydraulic analysis of the reach indicated that two of the three mid-channel bars located in the middle and left branch channels consist of gravels and cobbles and that a condition of incipient motion is attained at a range of discharge between 79 and 227 m^3/s at these bars.

3.6.4 Vertical Accretion of Banks and Channel Narrowing

Flow regulation reduces the dynamics of sediment deposition and erosion patterns. Each year, sediment deposits exposed during base flows are colonized by vegetation, and if these areas are not scoured by subsequent floods, a process of channel narrowing and increasing bank elevation can occur. At some point, this process becomes difficult to reverse because older, deeper-rooted vegetation is difficult to remove by all but the most extreme flood events.

Andrews (1986) and Lyons et al. (1992) presented sediment budgets and channel-width data for portions of the Green River during pre-dam and post-dam periods. Flaming Gorge Dam has affected the quantity of sediment transported by a given flow as a result of altering the channel morphology and/or the availability of sediment within the channel. Historic wet and dry periods also influence these factors.

Andrews (1986) described a sequence of degradation, equilibrium, and aggradation downstream from Flaming Gorge Dam that has developed in response to flow and sediment regulation by the dam. The degrading portion of the Green River channel, where sediment outflow exceeds sediment inflow, occurs just below Flaming Gorge Dam in Reach 1. Equilibrium conditions, where sediment inflow equals sediment outflow, occur in Reach 2. Aggradation (where sediment inflow is greater than sediment outflow) occurs in Reach 3, especially just downstream of the White River and Duchesne River confluences.

Andrews (1986) described channel narrowing in Reach 2 as a response to changes in sediment load and flooding caused by Flaming Gorge Dam operations. He determined that, on average, the channel had narrowed by 13% from 213 to 186 m since dam closure and that further narrowing would continue for another 30 years. Lyons et al. (1992) conducted additional analyses and arrived at somewhat different conclusions. Their results indicated that, in Reach 2, channel narrowing in response to construction of the dam had been completed by 1974 and produced a reduction from 217 to 204 m (6% reduction). The large floods from 1983 to 1986 reversed some of this narrowing and produced an average channel width of 208 m (4% reduction from pre-dam width).

Merritt and Cooper (1998) provided additional information on channel changes in Browns Park in Reach 1 following regulation by Flaming Gorge Dam. Three stages of channel change were identified by these authors, who used historic aerial photography and measurements of channel shape over a 30-year span after closure of Flaming Gorge Dam. Stage 1 (channel narrowing and development of banks) is similar to the degradation conditions described for Reach 1 by Andrews (1986). Stage 2 (channel widening, subaqueous bar formation, braided channel) was observed from a study of aerial photography from 1977, 1984, and 1994. Stage 3 (bar stabilization, fluvial marsh development, and continued channel widening) has been observed since 1994. Merritt and Cooper (1998) projected that channel widening in Browns Park could continue for several decades but that coalescence of islands will lead to formation of a smaller meandering channel over a longer time span.

Grams and Schmidt (1999), in addition to providing a description of the geomorphic characteristics of Reach 1 and portions of Reach 2, developed estimates of pertinent sediment-transport parameters for a range of channel conditions. Their estimates of average boundary shear stress during floods and critical shear stress of gravel bars show that the channel gradient and bar-material size in both the canyon and meandering portions of Reach 1 are in approximate adjustment with pre-Flaming Gorge Dam flood conditions. Although the river flows alternately through sections of extremely different geomorphic character, a near-equilibrium condition, where river morphology is adjusted to sediment and water inflow, exists throughout Reach 1.

Martin et al. (1998) described the redistribution of sand in Lodore Canyon during a 3-year study (1995 to 1997) of this portion of Reach 1. During their study, two periods of releases greater than power plant capacity (130 m^3/s) occurred — a 3-day event that reached a peak of 187 m^3/s on May 30, 1997, and a 6-day event that reached a peak of 244 m^3/s on June 17, 1997. Measurements indicated that sediment transport at 244 m^3/s was more than 3 times higher than transport at 130 m^3/s. The magnitude of scour and fill observed after these high flows was large relative to the topographic change that occurred, which indicated significant redistribution of sand. More deposition and erosion occurred during the 244-m^3/s event than during the 187-m^3/s event.

The net effect of the two high releases was significant erosion on the offshore portions of eddy sandbars and significant deposition on the onshore portions of sandbars at the stage of 130 m^3/s and higher flows. The initial peak of 187 m^3/s caused net offshore deposition, but the second peak of 244 m^3/s caused net offshore erosion. Aerial photographs confirmed that net deposition of sand occurred at higher elevations and that the long-term trend of channel narrowing and vegetation encroachment of low-elevation deposits had somewhat reversed.

Orchard and Schmidt (2000) determined that the active channel through Desolation and Gray Canyons decreased an average of 19% since the beginning of the century. They identified two episodes of channel narrowing as evidenced by two new surfaces along the channel. The cottonwood terrace is an abandoned floodplain that began to stabilize between 1922 and 1936 as a result of drier weather conditions. After closure of Flaming Gorge Dam, a second lower surface has become densely colonized by riparian vegetation and is accumulating sediment through vertical accretion. This process is continuing and appears to be contributing to the loss of in-channel fish habitat.

Allred (1997) studied channel narrowing and vertical accretion in the Green River at the Green River, Utah, gage and described the process by which in-channel deposits become stabilized. The stabilization process included the following steps: (1) emplacement and accretion of a lateral bar as large amounts of sediment are moved through the system, (2) low flood magnitude in years following bar emplacement, (3) rapid encroachment of riparian vegetation onto the exposed bar surface, (4) stabilization of the bar through extensive root system development, and (5) continued vertical accretion of the bar surface during periods of inundation when existing vegetation captures additional sediment.

Channel narrowing at this location occurred from 1930 to 1938; rapid accretion occurred from 1957 to 1962; and further narrowing occurred after 1962 (Allred 1997; Allred and Schmidt 1999). The 2-year flood decreased from 1,190 m^3/s for the period of 1895 to 1929, to 800 m^3/s between 1930 and 1957, and finally to 635 m^3/s after dam closure. This research indicates that channel narrowing occurred in response to weather changes and as vegetation (primarily tamarisk *Tamarix ramosissima*) invaded and stabilized newly formed inset floodplain deposits. The large floods of 1983 and 1984 did not reverse the narrowing trend at this site but instead resulted in the deposition of sediments at higher elevations.

O'Brien (1998) proposed in-channel maintenance flows for the Ouray portion of Reach 2 and the Canyonlands portion of Reach 3 on the basis of calculated incipient motion values for sand particles. These proposed in-channel maintenance flows would perform the physical process of reworking large sand bars and returning the sand to the deeper portions of the channel bed after the spring peak flow, thus preventing vegetation encroachment, bar attachment, and channel narrowing. Calculated in-channel maintenance flows ranged from 142 to 467 m^3/s (mean 235 m^3/s) in Reach 2 and 170 to 261 m^3/s (mean 208 m^3/s) in Reach 3 (O'Brien 1998). These moderate in-channel flows would assist in keeping the channel active, reworking in-channel sand bars, and reducing the impact of sediment deposition in sensitive habitat areas.

3.6.5 Floodplain Inundation

Floodplains develop along rivers where the valley floor is extensively covered with alluvium. The normal-flow channel, carved in the alluvium, is flanked by this low-relief surface that becomes part of the river bed during high-flow periods. Floodplains are primarily depositional landforms formed by lateral and vertical accretion of sediment deposits. These areas serve as important nursery and growth and conditioning habitats for endangered fishes in the Green River, particularly the razorback sucker. The frequency and extent of floodplain inundation vary considerably along the Green River and are largely a function of site-specific channel morphology (including the presence or absence of natural or manmade levees).

Irving and Burdick (1995) conducted an inventory, largely on the basis of aerial photography, of potential flooded bottomland habitats in the Green River. They determined that approximately 644, 3,500, and 3,300 ha were present in Reaches 1, 2, and 3, respectively. In

Reach 3, about 1,100 ha was present in the portion of the reach between the White River confluence and Pariette Draw and about 760 ha was present in Canyonlands. Irving and Burdick (1995) prioritized these bottomlands according to their value to endangered fishes and concluded that the highest priority bottomlands were in Reach 2 and upper Reach 3 (Escalante Ranch to Pariette Draw). They did not determine the relationship of floodplain inundation to flow.

Several areas along the Green River, including portions of the Ouray National Wildlife Refuge (NWR), Dinosaur National Monument, Canyonlands National Park, and a significant portion of Reach 2 in the Uinta Basin, have been studied to determine the relationship of flow to floodplain inundation (FLO Engineering, Inc. 1996, 1997; Bell et al. 1998; Cluer and Hammack 1999). Figure 3.18 illustrates this relationship in different study areas. The greatest area of floodplain habitat suitable for satisfying the life-history requirements of endangered fishes in the Green River system is located in the Ouray portion of Reach 2.

The investigation of floodplain-habitat inundation in the Ouray portion of Reach 2 by FLO Engineering, Inc. (1996) used the U.S. Army Corps of Engineers HEC-2 step backwater model to estimate water-surface profiles for a segment of river from RK 400 to 427. The model was used to estimate bankfull discharge and the relationship between flow and area of inundation. Under existing conditions at Ouray, the amount of floodplain inundation begins to increase rapidly as flows exceed about 527 m^3/s. With existing artificial levees removed, flooding would be initiated at flows between 368 and 453 m^3/s. Flooding in the Old Charlie Wash area, where a small side channel allows flooding of approximately 250 ha, begins at approximately 368 m^3/s. Other floodplain areas have inlet structures that are operational at flows of 85 to 113 m^3/s. If 0.6- to 0.9-m-deep side channels were excavated at certain locations, flooding of about 2,185 ha could be initiated in Ouray floodplain habitats at 368 m^3/s.

Flooding in the Island Park portion of Reach 2 (RK 530 to 535) was investigated by Cluer and Hammack (1999). They used numeric hydraulic modeling to evaluate the availability of various habitats over a range of flow conditions at this location. Inundated floodplain area increased from about 2 ha at 312 m^3/s to about 98 ha at 1,090 m^3/s.

Bell et al. (1998) used aerial photography to determine the relationship between flow and floodplain inundation in Reach 2 from Split Mountain Canyon to the White River (RK 396 to 505) and the upper portion of Reach 3 from the White River to Pariette Draw (RK 380 to 396). At 566 m^3/s, about 2,100 ha were flooded in Reach 2, about 3,500 ha were flooded at 624 m^3/s, and about 4,900 ha were flooded at 705 m^3/s.

Most of the floodplain habitat in Reach 3 is located in the upper portion of the reach just downstream of the confluences with the White and Duchesne Rivers, and this habitat is contiguous with the extensive floodplain habitats of Reach 2. In the upper portion of Reach 3 examined by Bell et al. (1998), the area of floodplain inundation was 265, 425, and 767 ha at 623, 680, and 920 m^3/s, respectively, as measured at the USGS gage near Green River, Utah (Figure 3.18). Downstream of this area, the river channel is more confined because of either resistant geology (Desolation, Gray,

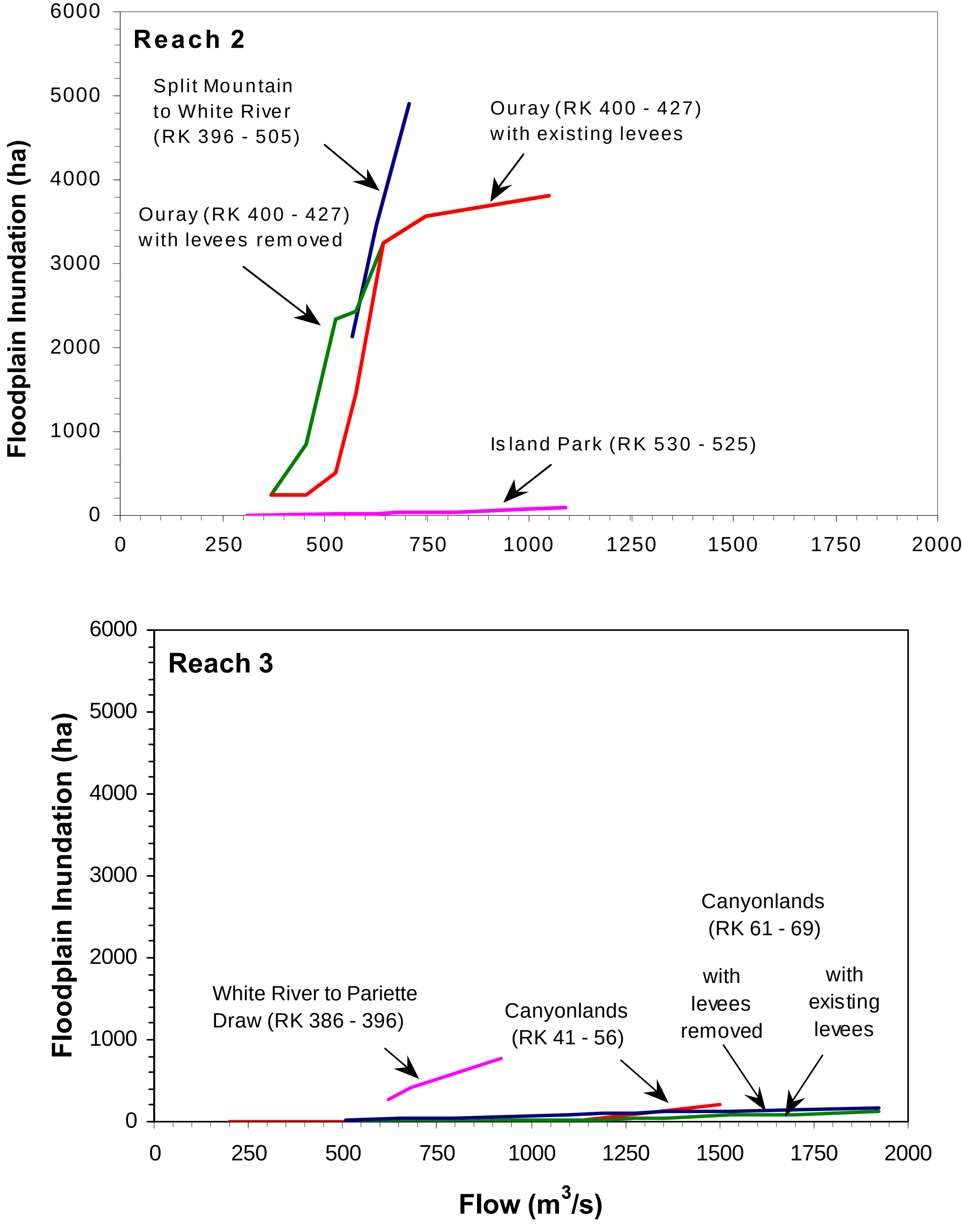


Figure 3.18.—Relationships between flow and floodplain habitat inundation in Reaches 2 and 3 of the Green River. Sources: Bell et al. (1998); FLO Engineering, Inc. (1996); Cluer and Hammack (1999)

and Labyrinth Canyons) or significant vertical accretion that has occurred in response to climatic change (see Section 3.6.4). Very little floodplain habitat is available even at very high flows.

FLO Engineering Inc. (1996) modeled inundation of floodplain habitats in Canyonlands National Park between RK 41 and 56 in Reach 3. Between 198 and 1,104 m^3/s, little change in the area of flooded habitat occurred. Between 1,104 and 1,500 m^3/s, the amount of flooded habitat increased from 2 to 200 ha (Figure 3.18). Another site in Reach 3 within Canyonlands National Park was studied by Cluer and Hammack (1999). These authors used HEC-RAS (a numeric model developed by the U.S. Army Corps of Engineers) to evaluate river-channel hydraulics for an 8-km study site located between RK 61 and 69. They described the floodplain in this portion of Reach 3 as a series of high, fairly continuous levees with basins and channels between the levees. At flows between 509 and 1,924 m^3/s, the amount of inundated floodplain would increase linearly from about 3 to about 130 ha. If existing levees were removed, the amount of inundated floodplain would increase linearly from 23 to 162 ha over this same range of flows.

Floodplain inundation in Reach 1 is not required to meet life-history needs (e.g., growth and conditioning habitat of larval fish) of any of the endangered fishes. Neither razorback sucker, Colorado pikeminnow, nor humpback chub are found upstream of or within Browns Park (where most floodplain habitats exist in Reach 1), nor are they expected to be found there because the cold temperatures of the water prevent their use of these areas. Consequently, floodplain inundation in Reach 1 is not an objective of the flow recommendations in this report.

3.7 SUMMARY OF RELATIONSHIPS BETWEEN FLOW, IN-CHANNEL HABITATS, AND FLOODPLAIN INUNDATION

Table 3.14 presents a summary of flow patterns and levels that, on the basis of our current understanding of the Green River system, would produce suitable habitat conditions for endangered fishes in the Green River downstream of Flaming Gorge Dam. The flows identified are those that have been demonstrated or estimated to restore dynamic hydrologic and geomorphologic processes that would maintain those habitats in areas designated as critical habitat or areas occupied by the endangered fishes. These flows are not the same for all portions of the river because tributary inputs and geologic changes along the river affect flow levels, seasonal patterns, channel hydraulics, bed characteristics, and sediment loads. Consequently, separate flow values are presented for each of the three reaches.

The availability and suitability of low-velocity backwater habitats during the base-flow period depend on flow, but their relationship to flow patterns and levels will change from year to year as a function of the elevation of sediment deposits behind which these habitats form. Because these elevations are set by preceding high flows and then eroded by subsequent flows, it is not possible to recommend a single flow that will optimize habitat area in all years. A specific recommendation for a given year would have to consider antecedent conditions, characteristics of in-channel sediment, and existing channel morphology.

Table 3.14.—Flows to maintain in-channel and floodplain processes relevant to the life-history needs of endangered fishes within three reaches of the Green River downstream of Flaming Gorge Dam.

Process	Flow Condition by Reach[a]		
	Reach 1	**Reach 2**	**Reach 3**
In-Channel Processes			
Establish low-velocity habitats (e.g., backwaters) during base-flow period.	Not applicable because of life history of fishes in reach.	Sand-bar topography, and therefore the availability of low-velocity habitats, changes annually in response to the passage of peak flows. As a result, no single base flow maximizes habitat availability under all conditions, and the range of measured optimal base flows varied from 35 to 140 m^3/s in the years studied. Large floods rebuild sand-bar topography and result in habitat availability being maximized at higher flows. Subsequent low-flood-peak years reduce the flow at which habitat availability is maximized. The duration of floods that are less than bankfull but greater than bar top should be minimized.	
Maintain levels of flow variability during the base-flow period comparable to those that occurred prior to dam construction.	Not applicable because of life history of fishes in reach.	Prior to dam construction, median coefficient of variation in base flows within a year was about 41% in summer and autumn and about 28% in winter. Between-day differences were about 3% pre-dam.	Not determined, but presumed similar to Reach 2.
Maintain in-channel habitats (redistribute sand deposits, prevent vegetation establishment on deposits and channel narrowing).	244 m^3/s caused some channel widening in Lodore Canyon and significant redistribu-tion of sand.	Flows that produce incipient motion of particles on existing deposits have been calculated as $\geq$ 235 m^3/s in the Ouray area.	Flows that produce incipient motion of particles on existing deposits have been calculated as $\geq$ 208 m^3/s in Canyonlands National Park.
Maintain clean spawning substrates.	Flows $\geq$ 244 m^3/s could provide suitable substrates for potential Colorado pikeminnow spawning in Lodore Canyon; Colorado pikeminnow do not currently spawn in Lodore Canyon.	Sedimentation of spawning bar at RK 504 occurs at flows >340 m^3/s; subsequent flows <200 m^3/s flush sediment.	Near the head of Gray Canyon, sediments flushed at flows between 79 and 227 m^3/s.

Table 3.14.—Continued.

Process	Flow Condition by Reach[a]		
	Reach 1	**Reach 2**	**Reach 3**
Floodplain Processes			
Inundate floodplain with levees in place.	Not applicable because of life-history needs of fishes in reach.	Significant flooding is initiated in the Ouray area at 527 m^3/s (514 ha); 1,457 ha becomes inundated at 575 m^3/s; 3,238 ha becomes inundated at 643 m^3/s; 3,561 ha becomes inundated at 748 m^3/s. In the Island Park area, 98 ha of floodplain becomes inundated at 1,090 m^3/s.	From White River to Pariette Draw, 265 ha of floodplain becomes inundated at 623 m^3/s; 425 ha at 680 m^3/s; and 767 ha at 920 m^3/s. Flooding is initiated in Canyonlands National Park between RK 41 and 56 at 1,104 m^3/s; the highest level of inundation is estimated at 200 ha at 1,500 m^3/s. At flows of 509–1,924 m^3/s, the amount of inundated floodplain increases linearly from about 3 to about 130 ha between RK 61 and 69.
Inundate floodplain with levees removed.	Not applicable because of life history of fishes in reach.	Flooding would be initiated at 368 to 453 m^3/s in the Ouray area.	23 ha would be flooded at 509 m^3/s in Canyonlands National Park between RK 61 and 69.

[a] River reaches: (1) Flaming Gorge Dam to Yampa River confluence, (2) Yampa River confluence to White River confluence, and (3) White River confluence to Colorado River confluence.

Peak flows scour and rearrange sediment deposits within the channel. An important factor in maintaining sediment-transport and depositional dynamics (and therefore preventing vegetation encroachment, channel narrowing, and vertical accretion of deposits and banks) is maintaining some degree of variability in annual peak flows as occurred prior to regulation. This can be achieved by linking peak releases to hydrologic conditions within the basin for any given year.

Providing suitable spawning substrates within the channel requires maintenance of dynamic sediment processes as well. Cobble and gravel deposits that are used for spawning are formed at very high flows. Lower peak flows result in deposition of fine sediments on these spawning areas, which are subsequently flushed as the flow level drops. Variability in peak flows whose timing coincides with the natural runoff cycle is needed to ensure suitable sites are available during the spawning period.

Restoration of floodplain habitats could be achieved through a combination of increased peak flows, prolonged peak-flow duration, lower bank or levee heights, and constructed inlets. The required flow level for inundation of floodplain habitat areas varies by reach, but the greatest possibility for inundation occurs in Reach 2 within the Ouray portion of the river. Flows of 527 m^3/s are needed to begin inundation of floodplain habitats (514 ha flooded at this level); flows of 643 m^3/s result in 3,240 ha of inundated floodplain habitat. If existing levees were removed, lower flows (between 368 and 453 m^3/s) would produce flooding in Reach 2. Inundating floodplain habitat in the lower portions of Reach 3 is problematic because of the vertical accretion (and natural levee formation) that has occurred. Very high peak flows (greater than 1,104 m^3/s) would be needed to overtop the banks in this reach, and the degree of floodplain inundation would be relatively minor even at higher flows.

The magnitude of peak flows in Reaches 2 and 3 can be maximized by linking the peak release from Flaming Gorge Dam with spring peak and immediate post-peak flows of the Yampa River. Because the drainage basins of the Yampa and upper Green Rivers have different characteristics, the timings of peak runoff within the two basins do not always coincide, but the resulting higher peaks would increase the effectiveness of the peak flow in restoring in-channel processes and inundating floodplain habitats.

4 FISHES OF THE GREEN RIVER

The major physical disruption to native fishes and their habitats in the main-stem Green River was caused by the construction and operation of Flaming Gorge Dam (Section 1.2.1). The fish community downstream of the dam, which consists of trout and native and nonnative cool-water and warm-water species, is strongly affected by water releases from the dam and the inflow of the Yampa River at Echo Park. With the exception of usually minor flow contributions from tributaries, the flow and temperature of the Green River upstream of the Yampa River are completely regulated by the dam. Releases of cold, clear water allowed for the establishment of a tailwater trout fishery and eliminated most, if not all, successful reproduction by most native fishes. Downstream of Echo Park, the Green River is more similar in flow, sediment loads, and temperature to pre-dam conditions because of the inflowing Yampa River. Trout become incidental to rare, and native and nonnative warm-water species become the major components of the fish community.

This chapter describes the fish fauna of the Green River from Flaming Gorge Dam downstream to its confluence with the Colorado River, with an emphasis on the endangered humpback chub, Colorado pikeminnow, and razorback sucker. The chapter is divided into four main sections. The first (Section 4.1), is an overview of the distribution, qualitative relative abundance, and habitats of the native and nonnative fishes that provides a general characterization of the overall fish community. The last three sections present detailed accounts of the ecology and habitat requirements of Colorado pikeminnow (Section 4.2), razorback sucker (4.3), and humpback chub (4.4). Information presented in these three sections was used to develop the integrated flow and temperature recommendations (Chapter 5) to ensure that the habitat needs of the endangered fishes are met.

Although the species accounts (Sections 4.2–4.4) are organized similarly, their content and format do vary because different levels of ecological information were available. Brief overviews of rangewide historic and present distributions, reasons for decline, and life-history attributes are followed by a summary of research on the species in the Green River system, including studies conducted in support of the 1992 Biological Opinion (USFWS 1992) and this synthesis report.

A description of the species' ecology in the Green River system is the centerpiece of each account. Each account begins with a discussion of the changes in distribution and abundance patterns associated with the construction and operation of Flaming Gorge Dam. Unique to the Colorado pikeminnow account (Section 4.2) is a conceptual model describing a range of factors that may currently affect the fish's growth, survival, and recruitment. Information on the life history of each species is presented by season — spring (21 March to 20 June), summer/autumn (21 June to 20 December), and winter (21 December to 20 March) — because distinct biological processes occur in each seasonal period. The Colorado pikeminnow account includes discussions of recruitment dynamics (long-term monitoring data are used to describe abundance trends for several life stages) and enhancement of thermal regimes to benefit the species.

Important seasonal flow-habitat relationships elucidated from life-history requirements are presented last in each species account. The flow and temperature needs of the species and expected benefits of flow and temperature modifications are elaborated for three reaches of the Green River (Figure 2.1) in a summary table.

4.1 OVERVIEW

4.1.1 Native Fishes

A total of 12 native fish species in four families has been reported from reaches of the main-stem Green River between Flaming Gorge Dam and the Colorado River confluence (Figure 2.1) and from lower portions of tributaries (Table 4.1). This assemblage of fishes can be partitioned into three categories by grouping species with similar environmental preferences or requirements. The three categories are: (1) warm-water species preferring or requiring large-river habitats, (2) species preferring cool- or cold-water streams or smaller river channels, and (3) species with more generalized habitat requirements. Species in the first category are the so-called "big-river" fishes endemic to the Colorado River basin and include humpback chub, bonytail, Colorado pikeminnow, flannelmouth sucker, and razorback sucker. The distribution and abundance of these fishes have been reduced considerably as a result of human alterations of native riverine habitats (e.g., the construction and operation of main-stream dams and the introduction of nonnative fish species) throughout significant portions of their respective ranges (Carlson and Muth 1989). The flannelmouth sucker is the only member of this group that is not federally listed as endangered and that is still common to abundant in many locations. In contrast, the once widespread and abundant bonytail now exists in the wild as a few scattered individuals and is considered functionally extinct. In the Green River system, the big-river fishes are generally restricted to warm-water reaches of the main-stem or middle–lower portions of larger tributaries.

The second category includes mountain sucker, Colorado River cutthroat trout, mountain whitefish, and mottled sculpin. These fishes prefer cool or cold water and are distributed primarily in upper or headwater sections of streams and rivers. In the main-stem Green River near or upstream of the Yampa River confluence, mountain suckers and mountain whitefish are incidental to rare, mottled sculpins are rare to common, and cutthroat trout are common in the tailwaters of Flaming Gorge Dam (where they are stocked).

Species in the third category are among the most widely distributed and abundant fishes in the Green River system and include roundtail chub, speckled dace, and bluehead sucker. Roundtail chubs occupy small to large river channels with warmer water. Although widespread in the Green River, roundtail chubs are rare in many main-stem Green River reaches (i.e., Reach 1, alluvial sections of Reach 2, and lower Reach 3). Habitats of speckled dace and bluehead sucker range from cool, clear streams to warm, turbid rivers, and these fishes are generally common to abundant in the Green River from Browns Park downstream.

Table 4.1.—Native fishes in the Green River between Flaming Gorge Dam and the Colorado River confluence.

Family and Common Name	Scientific Name	Present Distribution in the Green River System and Comments[a]
Cyprinidae		
Humpback chub	*Gila cypha*	Federally listed as endangered. Population concentrations are located in the Green River in Desolation and Gray Canyons and the Yampa River in Yampa Canyon. The fish is incidental in the Green River in Whirlpool and Split Mountain Canyons; in the Yampa River in Cross Mountain Canyon; and in the lower Little Snake River. Highly adapted to life in canyon environments. Adult habitat includes deep pools and shoreline eddies; young occupy warm, quiet habitats such as backwaters and eddies.
Bonytail	*Gila elegans*	Federally listed as endangered. It is considered extirpated in the Green River system but may persist in extremely low numbers in the main stem. It is considered adapted to main-stem rivers, where it has been observed in pools and eddies.
Roundtail chub	*Gila robusta*	Widespread, found in streams and rivers with warmer water. It is generally rare in the middle and extreme lower Green River; common to abundant elsewhere. Adult habitat includes riffles, runs, pools, eddies, and backwaters with silt-cobble substrate and adjacent to higher-velocity areas. Young occupy low-velocity shoreline habitats.
Colorado pikeminnow	*Ptychocheilus lucius*	Federally listed as endangered. It is widely distributed in warm-water reaches of the Green River and lower sections of larger tributaries. Adult habitat includes deep, low-velocity runs, pools, and eddies or seasonally flooded lowlands. Young occupy low-velocity, shallow, shoreline habitats (e.g., backwaters).
Speckled dace[b]	*Rhinichthys osculus*[b]	Widespread, common to abundant. It occupies permanent or intermittent cool- or warm-water streams and rivers and small to large lakes. In streams and rivers, adults are generally found in shallow runs and riffles with rocky substrates. Young occupy low-velocity shoreline or seasonally flooded habitats.
Catostomidae		
Bluehead sucker	*Catostomus discobolus*	Widespread, common to abundant. It is found in a variety of habitats, ranging from cool, clear streams to warm, turbid rivers. Adults prefer deep riffles or shallow runs over rocky substrates. Young occupy low-velocity shoreline or seasonally flooded habitats.

Table 4.1.—Continued.

Family and Common Name	Scientific Name	Principal Distribution in the Green River System and Comments[a]
Catostomidae (Cont.)		
Flannelmouth sucker	*Catostomus latipinnis*	Widespread, common to abundant. It is found in warm-water reaches of larger river channels. Adults typically occupy pools and deeper runs, eddies, and shorelines. Young occupy low-velocity shoreline or seasonally flooded habitats.
Mountain sucker	*Catostomus platyrhynchus*	Incidental to rare in the Green River upstream of the Yampa River confluence and in headwaters of the Yampa and White Rivers; common in tributaries of the Duchesne, Price, and San Rafael Rivers. It prefers cool, clear streams with rocky substrates.
Razorback sucker	*Xyrauchen texanus*	Federally listed as endangered. It is found in warm-water reaches of the Green River and lower portions of major tributaries; it primarily occurs in flat-water sections of the middle Green River between the Duchesne and Yampa Rivers. Adult habitat includes runs, pools, eddies, and seasonally flooded lowlands. Young presumably require nursery habitat with quiet, warm, shallow water such as tributary mouths, backwaters, and especially floodplain wetlands.
Salmonidae		
Cutthroat trout[c]	*Oncorhynchus clarki*[c]	Rare to common in certain upstream river reaches (e.g., Green River downstream of Flaming Gorge Dam; stocked in tailwaters) or impoundments. It prefers cold, clear headwater streams.
Mountain whitefish	*Prosopium williamsoni*	Incidental to rare in the Green River upstream of the Yampa River confluence and in lower sections of the Yampa and White Rivers; common in upper sections of the Yampa, White, and Duchesne Rivers. It prefers streams and rivers with cool, swift water and gravel or rubble substrates.
Cottidae		
Mottled sculpin	*Cottus bairdi*	Rare to common in the Yampa, Duchesne, Price, and San Rafael Rivers and in the Green River near the Yampa River confluence. It prefers cool-water riffles and deep runs with rocky substrates in streams and rivers.

Table 4.1.—Continued.

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[a] Abundant = occurring in large numbers and consistently collected in a designated area; common = occurring in moderate numbers and frequently collected in a designated area; rare = occurring in low numbers, either in a restricted area or having a sporadic distribution over a larger area; incidental = occurring in very low numbers and known from only a few collections. Endangered species are defined in text box on page 1-1.

[b] The Kendall Warm Springs dace (*Rhinichthys osculus thermalis*) is a federally listed endangered subspecies restricted to Kendall Warm Springs in the upper Green River drainage, Wyoming.

[c] Includes native Colorado River cutthroat trout (*Oncorhynchus clarki pleuriticus*) and nonnative Snake River Yellowstone cutthroat trout (*Oncorhynchus clarki bouvieri*) and Bear Lake Bonneville cutthroat trout (*Oncorhynchus clarki utah*).

Sources: Behnke et al. (1982), Tyus et al. (1982a), Miller and Hubert (1990), Maddux et al. (1993), Muth and Nesler (1993), McAda et al. (1994a, 1994b, 1995, 1996, 1997), Hlohowskyj and Hayse (1995). Information also came from personal communications with T. E. Chart and K. D. Christopherson of the Utah Division of Wildlife Resources and T. Modde of the U.S. Fish and Wildlife Service.

Before construction of Flaming Gorge Dam, the Green River exhibited seasonal fluctuations in flow, and water temperatures ranged from near freezing to greater than 20°C (Vanicek et al. 1970). Warm-water reaches of the Green River in and downstream of Flaming Gorge Canyon supported native fishes (including humpback chub, bonytail, Colorado pikeminnow, and razorback sucker) and some nonnative fishes; most of these species were successfully reproducing in the river upstream of its confluence with the Yampa River (Vanicek et al. 1970; Holden and Stalnaker 1975a; Holden 1979, 1991). Trout were absent from this portion of the river (Holden and Crist 1981).

After closure of the dam, hypolimnetic releases of cold, clear water allowed for the establishment of a tailwater trout fishery and reduced or eliminated populations of warm-water-adapted fishes downstream to the Yampa River confluence (Holden and Crist 1981). An additional perturbation occurred in 1962, when 700–800 km of the Green River and its tributaries were treated with the fish toxicant rotenone. The goal of this controversial project was to remove unwanted "coarse" fishes and allow Flaming Gorge Reservoir and its inflowing streams to realize their full potential as trout fisheries (Miller 1963; Dexter 1965; Pearson et al. 1968). Downstream detoxification failed, and rare endemic fishes were killed in Dinosaur National Monument (Holden 1991). The present tailwater fish community consists of native Colorado River cutthroat trout and several subspecies (Table 4.1) or species (Section 4.1.2) of nonnative trout, which largely are maintained by stocking; nonnative brown trout reproduce throughout most of Reach 1.

Penstocks at Flaming Gorge Dam were modified in 1978 to permit withdrawal of warmer water from selected reservoir depths (Section 3.2), thereby increasing temperatures in the tailwaters and downstream to levels better suited for trout production and growth (Holden and Crist 1981; Modde et al. 1991). As a result, the growth rates of trout improved, and the fishery is now well-recognized for abundant, large fish. However, it is interesting to note that the temperature of tailwater releases, which are managed not to exceed 13°C, are well below the 17°C optimum temperature for growth of nonnative rainbow trout (Hokanson et al. 1977), the main species of interest in the tailwater fishery. Native fishes also benefitted from thermal enhancement of the Green River. Within 6 months after the penstock modifications, Holden and Crist (1981) documented re-invasion and reproduction by common warm-water native fishes and nonnative fishes in the Green River upstream of the Yampa River confluence. The presence of adult Colorado pikeminnow and razorback suckers was documented, but reproduction by either species was not observed, and humpback chubs and bonytails were not found. Filbert and Hawkins (1995) suggested that increasing the temperature of releases from Flaming Gorge Dam to levels greater than 13°C may improve thermal conditions for tailwater trout and for native fishes downstream.

4.1.2 Nonnative Fishes

A total of 25 nonnative fish species in nine families has been reported from reaches of the main-stem Green River between Flaming Gorge Dam and the Colorado River confluence and from lower portions of tributaries (see Table 4.2 at the end of this section). Of the cool- or warm-water nonnative fishes, red shiner, common carp, sand shiner, fathead minnow, and channel catfish are widespread and common to abundant; redside shiner, white sucker, black bullhead, northern pike, green sunfish, and smallmouth bass are locally rare to common in some river reaches or habitats; and grass carp, Utah chub, creek chub, Utah sucker, western mosquitofish, brook stickleback, bluegill, largemouth bass, black crappie, and walleye are incidental to rare. Salmonids are generally restricted to Reach 1 and are most abundant in the tailwaters of Flaming Gorge Dam.

Nonnative fishes dominate the ichthyofauna of Colorado River basin rivers and have been implicated as contributing to reductions in the distribution and abundance of native fishes as a result of competition and predation (Carlson and Muth 1989). Behnke and Benson (1983) attributed the dominance of nonnative fishes to dramatic changes in flow regimes, water quality, and habitat characteristics. They reported that water development has converted a turbulent, highly variable river system into a relatively stable system, with flow and temperature patterns that allowed for the proliferation of nonnative fish species. Hawkins and Nesler (1991) identified red shiner, common carp, fathead minnow, channel catfish, northern pike, and green sunfish as the nonnatives considered by Colorado River basin researchers to be of greatest concern because of their suspected or documented negative interactions with native fishes. Sand shiner, white sucker, black bullhead, smallmouth bass, and largemouth bass were identified by Hawkins and Nesler (1991) as nonnatives of increasing concern because of their increasing abundance, habitat preferences, and/or piscivorous habits. Life histories of nonnative fishes in the upper Colorado River basin and their potential effects on native fishes were reviewed by Lentsch et al. (1996b).

Lentsch et al. (1996b) and Tyus and Saunders (1996) presented options for controlling nonnative fishes in the upper Colorado River basin. Those options included more restrictive stocking protocols, reduction or elimination of escape from existing stocks, more liberalized harvest regulations, mechanical removal, chemical eradication, and management of flows to benefit native fishes and suppress the abundance of nonnative fishes. The last option is important in the context of this report because occasional high or very high spring flows, and summer conditions resulting from higher spring flows, have been correlated with reduced abundance of channel catfish (Chart and Lentsch 1999) and nonnative cyprinids in shoreline habitats of the Colorado, Yampa, Green, and San Juan Rivers (McAda and Kaeding 1989; Haines and Tyus 1990; Muth and Nesler 1993; Gido et al. 1997; McAda and Ryel 1999; Trammell and Chart 1999). Effects of high spring flows on many of the common native fish species have been neutral to positive (e.g., Muth and Nesler 1993; McAda and Ryel 1999), but short-term decreases of some native fishes, including Colorado pikeminnow, have been documented (Haines and Tyus 1990; Tyus and Haines 1991; McAda and Ryel 1999). Exact mechanisms for lowered abundance of nonnative fishes associated with higher spring flows are unknown but may include (1) flushing fish downstream; (2) reducing their ability to successfully reproduce (high flows that persist later into the summer are often cold and may also reduce the abundance of warm-water nonnative fishes by inhibiting early spawning or reducing hatching success [Muth and Nesler 1993]); (3) reducing backwater habitat where many of these species complete their entire life cycle; or (4) a combination of the three mechanisms. Concerns exist within the Recovery Program about overbank flooding associated with high spring flows and the potential beneficial effects of floodplain inundation on the abundance of nonnative fishes in rivers. Preliminary conclusions by Crowl et al. (1998b) indicate that although the density of nonnative fishes in the middle Green River exhibited localized increases associated with floodplain inundation and draining, those increases were temporary. They also reported that preliminary evidence suggests patterns of weak, inconsistent interactions between native and nonnative fishes in floodplain sites.

Table 4.2.—Nonnative fishes in the Green River between Flaming Gorge Dam and the Colorado River confluence.

Family and Common Name	Scientific Name	Present Distribution in the Green River System and Comments[a]
Cyprinidae		
Grass carp	*Ctenopharyngodon idella*	Incidental in the lower Green River. It is adapted to warm, large rivers with moderate diversity of habitats.
Red shiner	*Cyprinella lutrensis*	Widespread, common to abundant. Its principal distribution is in middle and lower sections of larger rivers having warm and usually turbid water. It inhabits perennial or ephemeral riverine habitats and is tolerant of environmental extremes. It is the predominant species in nursery habitats of warm-water native fishes.
Common carp[b]	*Cyprinus carpio*[b]	Widespread, common to abundant. It is locally abundant in impoundments, slack-water riverine habitats, and seasonally flooded habitats. It prefers sheltered habitats with an abundance of aquatic vegetation in warm-water lakes, reservoirs, and rivers.
Utah chub	*Gila atraria*	Incidental to rare in the Green River downstream of Flaming Gorge Dam to the Yampa River confluence, and in the lower Yampa River, Duchesne River drainage, and Price River. It is abundant in Flaming Gorge Reservoir. It prefers littoral and pelagic zones of reservoirs; it is generally not found in larger rivers.
Sand shiner	*Notropis stramineus*	Common to abundant in the middle and lower sections of the Yampa and Green Rivers and the warm-water reaches of other tributaries. It prefers small- to large-sized streams and rivers with permanent flow, seasonally warm water, slow to moderate water velocities, and clear to turbid water. It is commonly found in nursery habitats of warm-water native fishes.
Fathead minnow[b]	*Pimephales promelas*[b]	Widespread, common to abundant in middle and lower sections of larger rivers having warm and usually turbid water. It inhabits a variety of habitats in ponds, lakes, reservoirs, streams, and rivers. It is commonly found in nursery habitats of warm-water native fishes.
Redside shiner[b]	*Richardsonius balteatus*[b]	Rare to common in the Yampa River and upper sections of the Green and Duchesne Rivers. It prefers cool water and is found in a variety of habitats. In streams, it may occur in slow to swift, clear to turbid water and over cobble, gravel, sand, clay, or mud substrates; it is frequently found associated with vegetation.

Table 4.2.—Continued.

Family and Common Name	Scientific Name	Present Distribution in the Green River System and Comments[a]
Cyprinidae (Cont.)		
Creek chub	*Semotilus atromaculatus*	Mostly incidental to rare with a very sporadic distribution. It prefers small streams with clear, cool water, moderate to high gradients, gravel substrate, and well-defined riffles and pools with abundant cover.
Catostomidae		
Utah sucker	*Catostomus ardens*	Rare, occurs primarily in the Strawberry and Duchesne Rivers. It prefers reservoirs or quiet waters in rivers with cobble or gravel substrates and emergent vegetation.
White sucker	*Catostomus commersoni*	Rare to common in reaches of the Yampa River and in upper and middle sections of the Green River; abundant in Flaming Gorge Reservoir. It is a habitat generalist found in lakes, reservoirs, streams, and rivers. In streams and rivers, it prefers deep riffles, pools, and shallow runs over gravel or cobble substrates.
Ictaluridae		
Black bullhead[b]	*Ameiurus melas*[b]	Sporadic distribution in middle and lower sections of the Green, Yampa, Duchesne, and White Rivers. It is incidental to rare in main-channel habitats; common to abundant in inundated floodplain habitat adjacent to the middle Green River. It is found in turbid backwaters, seasonally flooded habitats, impoundments, and low-gradient river reaches with muddy bottoms.
Channel catfish[b]	*Ictalurus punctatus*[b]	Widespread, common to abundant in middle and lower sections of larger rivers. Its optimum riverine habitat has warm water and a diversity of velocities, depths, and structural features that provide cover and feeding areas. In the Green and Yampa Rivers, it is most abundant in rocky, turbulent, high-gradient canyon habitats.
Escocidae		
Northern pike	*Esox lucius*	Occurs in several rivers and impoundments but is infrequently collected, except in reaches of the Yampa River and middle Green River, where it is often caught during spring sampling for adult Colorado pikeminnow and razorback suckers. It primarily inhabits vegetated ponds, marshes, larger lakes, and deep pools, eddies, mouths of tributaries, and seasonally flooded habitats of larger rivers.

Table 4.2.—Continued.

Family and Common Name	Scientific Name	Present Distribution in the Green River System and Comments[a]
Salmonidae		
Rainbow trout	*Oncorhynchus mykiss*	Common to abundant in the Green River upstream of the Yampa River confluence (stocked in Flaming Gorge Dam tailwaters), incidental to rare downstream; common to abundant in upper sections of the Yampa, Duchesne, and White River drainages. It prefers pools, eddies, runs, and riffles in streams with gravel or cobble substrates.
Kokanee	*Oncorhynchus nerka*	Common in Flaming Gorge Reservoir and upstream; rare in tailwaters, where it is a probable escapee from the reservoir. It prefers pelagic zones of reservoirs.
Brown trout	*Salmo trutta*	Rare to common in the Green River upstream of the Yampa River confluence and in upper sections of the Duchesne River drainage; rare in the Yampa and White Rivers. It prefers deep pools, riffles, and runs with sand or cobble substrates and moderate to fast current.
Brook trout	*Salvelinus fontinalis*	Rare to common in the Green River upstream of the Yampa River confluence (stocked in Flaming Gorge Dam tailwaters) and in Soldier Creek and Strawberry Reservoirs; found in headwater areas of tributaries. It prefers clear headwater streams with gravel substrate.
Poeciliidae		
Western mosquitofish	*Gambusia affinis*	Incidental to rare, very sporadic distribution. It prefers warm, slack-water areas.
Gasterosteidae		
Brook stickleback	*Culaea inconstans*	Incidental in the upper Yampa River drainages and in the middle Green River between Jensen and Ouray, Utah (almost exclusively in floodplain habitat). It prefers clear, cool densely vegetated waters of slow-flowing small streams or ponds.
Centrarchidae		
Green sunfish	*Lepomis cyanellus*	Generally rare in the middle Green and lower Yampa, Duchesne, and White Rivers; locally common in the Green River near the confluences of the Duchesne and White Rivers and in adjacent inundated floodplain habitat. It prefers backwater areas of warm-water streams or weed beds in warm-water lakes and reservoirs.

Table 4.2.—Continued.

Family And Common Name	Scientific Name	Present Distribution in The Green River System And Comments[a]
Centrarchidae (Cont.)		
Bluegill	*Lepomis macrochirus*	Incidental. It prefers shallow, warm lakes and ponds or slow-moving areas of clear streams with abundant aquatic vegetation.
Smallmouth bass	*Micropterus dolomieui*	Generally rare along the Green River in Utah but common in areas near the confluences of the Duchesne and White Rivers; generally rare in the middle and lower Yampa River but may be locally common in some areas. It prefers clear, wide, fast-flowing runs and flowing pools with gravel or rubble substrates.
Largemouth bass	*Micropterus salmoides*	Incidental in the lower Yampa River and in the Green River downstream of the Yampa River confluence; rare in Flaming Gorge Reservoir. It prefers clear, quiet waters in rivers with aquatic vegetation or vegetated littoral zones in lakes and reservoirs.
Black crappie	*Pomoxis nigromaculatus*	Incidental in the Green River near the confluences of the Duchesne and White Rivers. It inhabits clear, warm, quiet waters of ponds, lakes, and backwaters of larger rivers; it is generally found where there is abundant aquatic vegetation.
Percidae		
Walleye[b]	*Stizostedion vitreum*[b]	Incidental to rare in the Duchesne River; incidental in the Yampa and middle Green Rivers (often found in slow, shallow runs, usually associated with emergent or bank vegetation). It prefers large streams, rivers, and lakes with moderately deep, clear water.

[a] Abundant = occurring in large numbers and consistently collected in a designated area; common = occurring in moderate numbers and frequently collected in a designated area; rare = occurring in low numbers, either in a restricted area or having a sporadic distribution over a larger area; incidental = occurring in very low numbers and known from only a few collections.

[b] Reported from the Green River between Flaming Gorge and Split Mountain Canyon before closure of Flaming Gorge Dam (Vanicek et al. 1970).

Sources: Behnke et al. (1982), Tyus et al. (1982a), Miller and Hubert (1990), Muth and Nesler (1993), McAda et al. (1994a, 1994b, 1995, 1996, 1997), Hlohowskyj and Hayse (1995), Lentsch et al. (1996b), Modde and Haines (1996). Personal communications: T. E. Chart and K. D. Christopherson, Utah Division of Wildlife Resources; J. A. Hawkins, Colorado State University Larval Fish Laboratory; T. Modde, U.S. Fish and Wildlife Service.

4.2 COLORADO PIKEMINNOW

4.2.1 Distribution and Status Overview

The endangered Colorado pikeminnow is endemic to the Colorado River basin and was formerly widespread and abundant in warm-water streams and rivers (Jordan and Evermann 1896). Historic accounts suggest that Colorado pikeminnow were especially abundant in the lower Colorado River basin (Figure 1.1) downstream of Lees Ferry, Arizona (Minckley 1973; Tyus 1991a; Maddux et al. 1993). Lower basin populations remained abundant until the 1930s (Miller 1961) but declined soon thereafter presumably as a result of the combined effects of river regulation by dams and introduced fishes (Minckley and Deacon 1968; Minckley 1973). The last Colorado pikeminnow collected in the Gila River system was collected in 1950; scattered individuals were captured in the lower main-stem Colorado River and reservoirs in the 1960s (Minckley 1973), but by the early 1970s, the species was extirpated from the lower Colorado River basin (Tyus 1991a). In the upper Colorado River basin, historic accounts also report the presence of large populations of Colorado pikeminnow (Tyus 1991a; Quarterone 1993). Colorado pikeminnow persist in all three major river and tributary systems of the upper basin (i.e., San Juan, Colorado, and Green River systems), but populations are severely reduced in all but the latter (Platania et al. 1991; Tyus 1991a; Osmundson and Burnham 1996). There may be less than 100 wild adult Colorado pikeminnow remaining in the San Juan River system, considering the few recent captures and relatively high recapture rates (D. L. Propst, New Mexico Department of Game and Fish, personal communication). Osmundson and Burnham (1996) recently estimated that about 600 to 650 adult Colorado pikeminnow occur in the Colorado River upstream of the Green River confluence. Although no abundance estimates have been calculated, populations in the Green River system are thought to be substantially larger than those in the Colorado River on the basis of relative capture-rate data collected annually in the ISMP and capture rates of marked fish (Tyus 1991a; McAda et al. 1994a,b, 1995, 1996, 1997).

Critical habitat designated for Colorado pikeminnow makes up only about 29% of the species' original range and occurs exclusively in the upper Colorado River basin (USFWS 1994). River reaches (including the 100-year floodplain) of critical habitat for Colorado pikeminnow in the Green River system include the Yampa River from Highway 394 bridge near Craig, Colorado, downstream to the Green River (about 210 km); Green River downstream of the Yampa River to the confluence with the Colorado River (about 555 km); and White River from Rio Blanco Reservoir downstream to the Green River (about 235 km).

4.2.2 Life History Overview

The large size, predaceous dietary habits, and complex life history of Colorado pikeminnow make it one of the most impressive fishes in North America. Historically, adult Colorado pikeminnow attained lengths of more than 1 m and individuals in excess of 20 kg were common (Minckley 1973; Tyus 1991a). Individuals longer than 0.8 m and heavier than 10 kg are now very uncommon and are likely older than 40 years (Tyus 1991a; Osmundson et al. 1997). Habitats of adult Colorado pikeminnow consist of deep, low-velocity eddies, pools, and runs, or seasonally flooded lowlands (Tyus 1990; Tyus 1991a). Adults mature at total lengths (TLs) exceeding 400 mm and at 5 to 7 years of age (Vanicek and Kramer 1969; Hamman 1981; Tyus 1991a). Adults sometimes migrate long distances to spawn. Round-trip distances of up to 950 km (Irving and Modde 2000) have been reported, and individuals may migrate to natal areas by using cues that were imprinted during their larval stage (Tyus 1985; Tyus 1990; Irving and Modde 2000). Colorado pikeminnow reproduce during late spring and summer after discharge from snowmelt runoff peaks and when water temperatures are increasing and generally greater than 16ºC (Haynes et al. 1984; Tyus 1990; Tyus 1991a; Bestgen et al. 1998). Following spawning, most adults return by late August or September to home ranges occupied the previous spring (Tyus 1990; Irving and Modde 2000).

Eggs deposited in spawning gravel hatch within 5–7 d, and larvae emerge from spawning substrate (swim up) 5–7 d later. At swim-up, larvae are 6–9 mm TL and are immediately swept downstream, sometimes long distances, away from spawning areas (Hamman 1981; Haynes et al. 1984; Nesler et al. 1988; Bestgen and Williams 1994; Bestgen et al. 1998). Larvae drift to relatively low-gradient river reaches where low-velocity, shallow, channel-margin habitats (e.g., backwaters) are common, and they remain there throughout the summer (Vanicek and Kramer 1969; Tyus and Haines 1991; Muth and Snyder 1995). Juveniles also occupy backwaters and other low-velocity nearshore areas. Older and larger subadults tend to use habitat similar to that of adults. Subadults then disperse to upstream reaches where they establish home ranges (Osmundson et al. 1998).

The ability to feed in turbid waters of the Colorado River system and the lack of jaw teeth are unusual features of Colorado pikeminnow. Individuals less than 50 mm TL eat primarily invertebrates; the diet of those between 50 and 200 mm TL is a combination of invertebrates and fish; and Colorado pikeminnow greater than 200 mm TL are mainly piscivorous (Vanicek and Kramer 1969; Muth and Snyder 1995). Large adults also occasionally consume other vertebrates including birds and mammals (Tyus 1991a). Life-history information gathered mostly since 1990 and specific to the Green River system is presented in greater detail in section 4.2.5.

4.2.3 Research on Colorado Pikeminnow for the 1992 Flaming Gorge Biological Opinion

Investigations conducted in support of the 1992 Biological Opinion on operation of Flaming Gorge Dam emphasized Colorado pikeminnow in the Green River system (Table 1.1). Primary topics were spring and early summer flow requirements for Colorado pikeminnow (Tyus 1990), backwater productivity and availability (Grabowski and Hiebert 1989; Pucherelli et al. 1990), summer and autumn requirements of early life stages of Colorado pikeminnow (Tyus and Karp 1989; Haines and Tyus 1990; Tyus 1991b; Tyus and Haines 1991), winter habitat and flows for young and adult Colorado pikeminnow (Valdez and Masslich 1989; Converse et al. 1999), and fish community interactions (Haines and Tyus 1990; Karp and Tyus 1990b; Tyus and Beard 1990; Tyus and Nikirk 1990). Several other studies (see Wick and Hawkins 1989; Karp and Tyus 1990a; Tyus and Karp

1991) were conducted prior to the Biological Opinion and supported the body of evidence used to make flow recommendations.

4.2.4 Research on Colorado Pikeminnow for the 1990–1996 Flaming Gorge Flow Recommendations Investigation

Research was conducted during 1990–1996 to support the Flaming Gorge Flow Recommendations Investigation. This research emphasized refinement of earlier studies on Colorado pikeminnow and focused mostly on reproduction, habitat needs of early life history stages, and recruitment and overwinter survival of early life stages (Bestgen and Williams 1994; Bestgen 1996, 1997; Bestgen and Bundy 1998; Bestgen et al. 1998; Converse et al. 1999; Chart et al. 1999; Day et al. 1999, 2000; Rakowski and Schmidt 1999). The effects of nonnative species and winter conditions on distribution, growth, and survival (Valdez 1995; Converse et al. 1999; Haines et al. 1998) and on the distribution and habitat of age-0 and adult life stages (Bestgen and Crist 2000; Chart and Lentsch 2000; Chart et al. 1999) were also studied.

Other contemporary studies either not funded under the Flaming Gorge Flow Recommendation Investigations or funded outside the Recovery Program provided additional information on backwater habitats and recruitment of early life stages (Wolz and Shiozawa 1995; Collins and Shiozawa 1996; Bestgen et al. 1997; Nance 1998; Irving and Modde 2000) and effects of nonnative fishes (Beyers et al. 1994; Tyus and Saunders 1996). Studies on distribution and abundance of adults (Hawkins et al. 1996; Cavalli 1999; USFWS 1998b) were conducted in parts of the system not directly affected by Flaming Gorge Dam.

4.2.5 Ecology of Colorado Pikeminnow in the Green River System

4.2.5.1 Distribution and Abundance

***Before Flaming Gorge Dam*.—**Although historic accounts are sketchy, most describe Colorado pikeminnow as widespread and abundant in the Green River system (Tyus 1991a; Quarterone 1993). On the basis of those accounts and habitat tolerances described in more recent studies, it is reasonable to assume that Colorado pikeminnow were found throughout lower reaches of most tributary streams in warm and cool water, and extended far upstream in the main-stem Green River to near Green River, Wyoming (Ellis 1914; Baxter and Simon 1970). In the vicinity of the Flaming Gorge Dam site, an aggregation of ripe male Colorado pikeminnow was discovered in early August 1961 (Vanicek et al. 1970), which made this area a likely location for reproduction.

***After Flaming Gorge Dam*.—**Closure of Flaming Gorge Dam dramatically altered the distribution and status of Colorado pikeminnow in the Green River upstream of the Yampa River. When the reservoir was filling from 1963 to 1967, dam releases were relatively low, water temperatures were relatively warm in two of those years (1963 and 1965), and reproduction by some native fishes was documented in the Green River upstream of the Yampa River confluence (Vanicek et al. 1970). Reproduction by Colorado pikeminnow, as evidenced by the presence of early life stages in collections, was noted only in the Green River between Echo Park and Jensen, Utah (Vanicek et al. 1970; Holden and Stalnaker 1975a, 1975b). Those Green River fish were likely the result of reproduction in the lower Yampa River (Haynes et al. 1984; Bestgen et al. 1998) and were relatively small and slow-growing because of cold dam releases (Vanicek and Kramer 1969).

The 1978 penstock modifications to Flaming Gorge Dam, which increased the temperature of releases, also affected fishes in downstream reaches. Immediately after modifications, Holden and Crist (1981) documented reproduction by common native species and invasion of other warm-water fishes into the Green River upstream of the Yampa River confluence. Adult Colorado pikeminnow were rare, and reproduction was not noted (Holden and Crist 1981). Those modifications did not result in reestablishment of early life stages of Colorado pikeminnow in backwaters of the Green River between the Yampa River confluence and Jensen, Utah, an area where they were once common (Vanicek et al. 1970; Holden and Stalnaker 1975a, 1975b).

By the time the first comprehensive surveys were conducted during 1967–1973 (Holden and Stalnaker 1975a, 1975b), the Colorado pikeminnow was considered rare and endangered throughout the upper Colorado River basin, including the Green River system. Holden and Stalnaker (1975a) identified the lower Yampa River in Yampa Canyon and the middle and lower Green River as potential spawning areas on the basis of aggregations of ripe adults and presence of early life stages. These inferences later proved mostly correct, since spawning areas have been found in the lower Yampa River and Green River in Gray Canyon (Haynes et al. 1984; Tyus 1990; Tyus and Haines 1991; Bestgen et al. 1998).

***Current distribution*.—**The current distribution of Colorado pikeminnow includes warm-water portions of the Green River and accessible lower reaches of most larger tributaries (Figure 4.1). However, distribution and abundance patterns are life-stage-specific and vary seasonally (Table 4.3; specific Green River reaches are defined in that table and in Chapters 2 and 3). The distribution and abundance patterns for various life stages of Colorado pikeminnow illustrate that habitats of different sizes and characteristics may be important in sustaining Colorado pikeminnow in the system. They also illustrate the importance of the main-stem Green River for all life-history stages of Colorado pikeminnow, because it contains one of two known spawning areas, nearly all age-0 and juvenile habitat, and the most extensive adult habitat.

Because of their mobility and environmental tolerances, adult Colorado pikeminnow are the most widely distributed pikeminnow of all life stages. Subadult and adult Colorado pikeminnow longer than 400 mm TL occur in the main-stem Green River from its confluence with the Colorado River upstream to at least the upper reaches of Lodore Canyon (Tyus et al. 1982b; Tyus 1991a; McAda et al. 1994a; Bestgen and Crist 2000). Adults also occur in the Yampa River upstream to near Craig, Colorado; in the White River upstream to Taylor Draw Dam and Kenney Reservoir; in the lower portions of the San Rafael and Duchesne Rivers (T. E. Chart, U.S. Bureau of Reclamation,

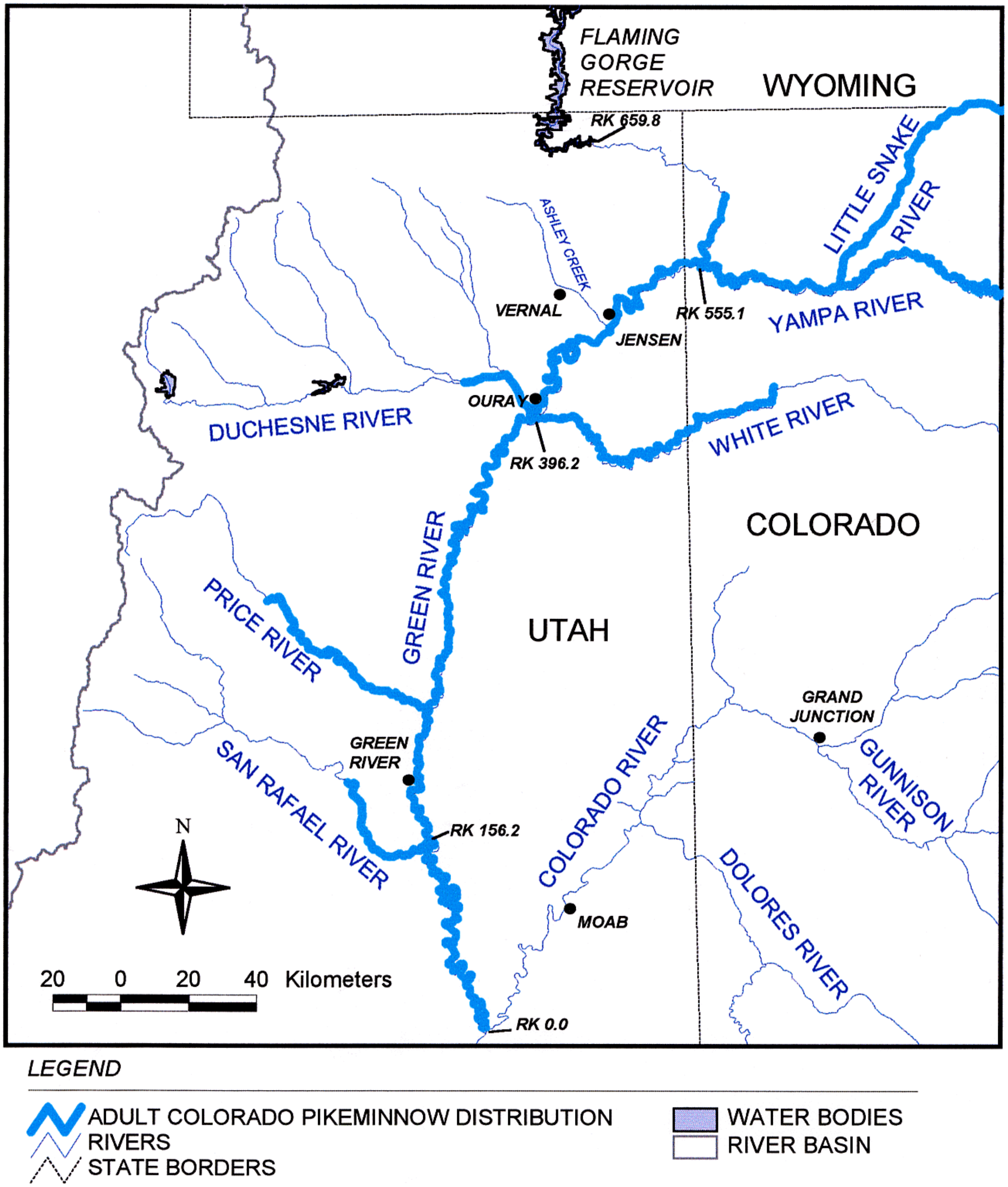


Figure 4.1—Present distribution of adult Colorado pikeminnow in the Green River system.

Table 4.3.—Distribution and abundance of various life stages of Colorado pikeminnow in the Green River system.[a]

Life Stage	River Reach[b]							
	Upper Yampa River	Lower Yampa River	Green River			White River	Duchesne River	Price River
			Reach 1	Reach 2	Reach 3			
Embryos		A			A			
Drifting larvae		A		A	A			
Age-0 fish in backwaters (10–80 mm TL)		R		C	A			
Juveniles (80–400 mm TL)		R		C	A	C	R	R
Adults (> 400 mm TL)	C	C	C	A	A	A	R	R

[a] Abundance of life stages present in various reaches was qualitatively ranked as abundant (A), common (C), or rare (R). Rankings were based on comparison of abundance data for each life stage among various reaches of the Green River system. Blank cells indicate absence of a life stage from a particular river or river reach. TL = total length.

[b] Upper Yampa River is upstream of Yampa Canyon, lower Yampa River is from the Green River confluence to the upstream end of Yampa Canyon, Green River Reach 1 is Flaming Gorge Dam to Yampa River confluence, Reach 2 is Yampa River confluence to White River confluence, and Reach 3 is White River confluence to Colorado River confluence.

Sources: Tyus et al. (1982b), Tyus and Haines (1991), McAda et al. (1994a, 1994b, 1995, 1996, 1997), Bestgen et al. (1998), and Cavalli (1999).

personal communication, and G. B. Haines, U.S. Fish and Wildlife Service, personal communication); and in the lower 143 km of the Price River (Cavalli 1999). Colorado pikeminnow are occasionally found in the Little Snake River from its Yampa River confluence upstream into Wyoming (Marsh et al. 1991; Wick et al. 1991). Formerly suitable habitats in upstream portions of the White River (Martinez 1986; Irving and Modde 2000) and Price River (Cavalli 1999) are no longer available because of impassable barriers. ISMP electrofishing data and other literature indicate that subadult and adult Colorado pikeminnow are most abundant in Reach 3 of the Green River, followed in order by Reach 2 of the Green River, the White River, the Yampa River, Reach 1 of the Green River, and the Price River. The Duchesne River (29 January 1999 annual progress report of the Duchesne River Fisheries Study) and San Rafael River (T. E. Chart, U.S. Bureau of Reclamation, personal communication) also support small populations of Colorado pikeminnow.

During most of the year, distribution patterns of adults in the Green River system are stable, and from late summer to the following spring, adults are widely distributed and occupy distinct home ranges (Tyus 1990; Tyus 1991a; Irving and Modde 2000). Distribution of adults changes in late spring and early summer, when most mature fish migrate to spawning areas (Figure 4.1) located in the lower Yampa River in Yampa Canyon and the lower Green River in Gray Canyon (Tyus and McAda 1984; Tyus 1985; Tyus 1990; Tyus 1991a; Irving and Modde 2000). Those fish remain in spawning areas for 3–8 weeks before returning to home ranges. Some radio-tagged fish did not migrate to spawning areas each year (Tyus 1990). These may have been immature or nonspawning individuals or fish that moved to other areas for spawning. Although spawning areas other than those in the lower Yampa and lower Green Rivers may exist (Tyus 1990), recent movement patterns of adults (Irving and Modde 2000) and capture rates of larvae at drift-net sites downstream of principal spawning areas (Bestgen et al. 1998) suggest that other sites are rarely used.

Similar to the distribution of adults, the distribution of early life stages of Colorado pikeminnow is dynamic on a seasonal basis and linked to habitat in the main-stem Green River downstream of spawning areas. Embryos occur in the substrate of spawning riffles at the two main canyon-bound spawning areas during the summer reproductive period. After hatching and emergence from spawning substrate, larvae are dispersed downstream by relatively swift, main-channel currents to lower-gradient alluvial or valley reaches where they occupy low-velocity channel margins and backwaters throughout the summer. A larva may drift for only a few days, but larvae occur in main channels of the lower Yampa River and the Green River for 3–8 weeks depending on length of the annual reproductive period (Nesler et al. 1988; Tyus and Haines 1991; Bestgen et al. 1998). The Yampa River spawning area consistently produces more larvae than the spawning area in the lower Green River (Bestgen et al. 1998).

At present, there are two primary reaches of Colorado pikeminnow nursery habitat in the Green River system. One occurs in the lower portion of Reach 2 of the middle Green River from near Jensen, Utah, downstream to the Duchesne River confluence. The other is in the lower portion of Reach 3 in the lower Green River from near Green River, Utah, downstream to the Colorado River confluence (Tyus and Haines 1991; McAda et al. 1994a, 1994b, 1995, 1996, 1997). Although the density of age-0 fish in autumn was usually higher in the lower Green River than in the middle Green

River (Tyus and Haines 1991; McAda et al. 1994a), differences in habitat quantity may have confounded abundance estimates based solely on fish density because more fish may have occupied the fewer backwaters present in Reach 3. The reach of the Green River defined mostly by Desolation and Gray Canyons (the remainder of Reach 3) also provides nursery habitat for Colorado pikeminnow (Tyus and Haines 1991; Day et al. 2000). Historically, Echo and Island Parks in the upper portion of Reach 2 supported nursery habitat for Colorado pikeminnow (Vanicek et al. 1970; Holden and Stalnaker 1975a; Holden and Crist 1981). Early life stages of Colorado pikeminnow in that area remain rare (Holden and Crist 1981; Tyus and Haines 1991; Bestgen and Crist 2000). No larvae or juveniles of Colorado pikeminnow have been collected from the Green River upstream of the Yampa River confluence since initial post-impoundment studies of Flaming Gorge Dam ended in 1966 (Vanicek and Kramer 1969; Vanicek et al. 1970; Holden and Crist 1981; Bestgen et al. 1998; Bestgen and Crist 2000).

Juvenile Colorado pikeminnow 80–400 mm TL have the most restricted distribution of any life stage in the Green River system. Juveniles are most common in the lower portion of Green River Reach 3 downstream of Green River, Utah, with fewer in Reach 2 (McAda et al. 1994a, 1994b, 1995, 1996, 1997). Juveniles are found in the White River and other tributaries (McAda et al. 1994b, 1995, 1996, 1997; Cavalli 1999), but few have ever been caught in the Yampa River upstream of Yampa Canyon. A few age-0 and juvenile Colorado pikeminnow were captured in recent years from the lower Yampa River and the Green River in the Island-Rainbow Park reach (Bestgen and Crist 2000; K. R. Bestgen, unpublished data).

***Factors affecting current distribution and abundance*.—**The distribution and abundance patterns of various life stages of Colorado pikeminnow in the Green River system change temporally and spatially each year. The multiple and interacting factors affecting distribution and abundance dynamics were generally described by a conceptual life-history model for Colorado pikeminnow (Figure 4.2) constructed by Bestgen et al. (1997). The conceptual model links recruitment at successive developmental stages and shows how abundance at each interval is affected by various biotic and abiotic controlling factors. The model illustrates how distribution, abundance, and recruitment patterns of Colorado pikeminnow and outcomes of management actions are potentially affected by multiple and interacting biotic and abiotic processes at different temporal scales. For example, the number of age-0 Colorado pikeminnow that survive to autumn may be a function of the number of larvae produced, their growth rates, predator density, and the quantity and the quality of backwaters available that summer. Predation, habitat selection, and climatic events that cause floods are factors that affect survival and growth on a daily basis. The model also conveys an annual temporal structure that begins with deposition of embryos in the substrate. Recognition of various temporal scales is important because it emphasizes that recruitment to a life stage is a function of numerous processes occurring at different times. It also emphasizes that in order to explain characteristics of a population, it might be necessary to study events that occurred days, months, years, or even decades ago. Similarly, the temporal aspect of life-history patterns of Colorado pikeminnow and the other endangered fishes suggests that detectable changes in population structure may not occur until well into the future.

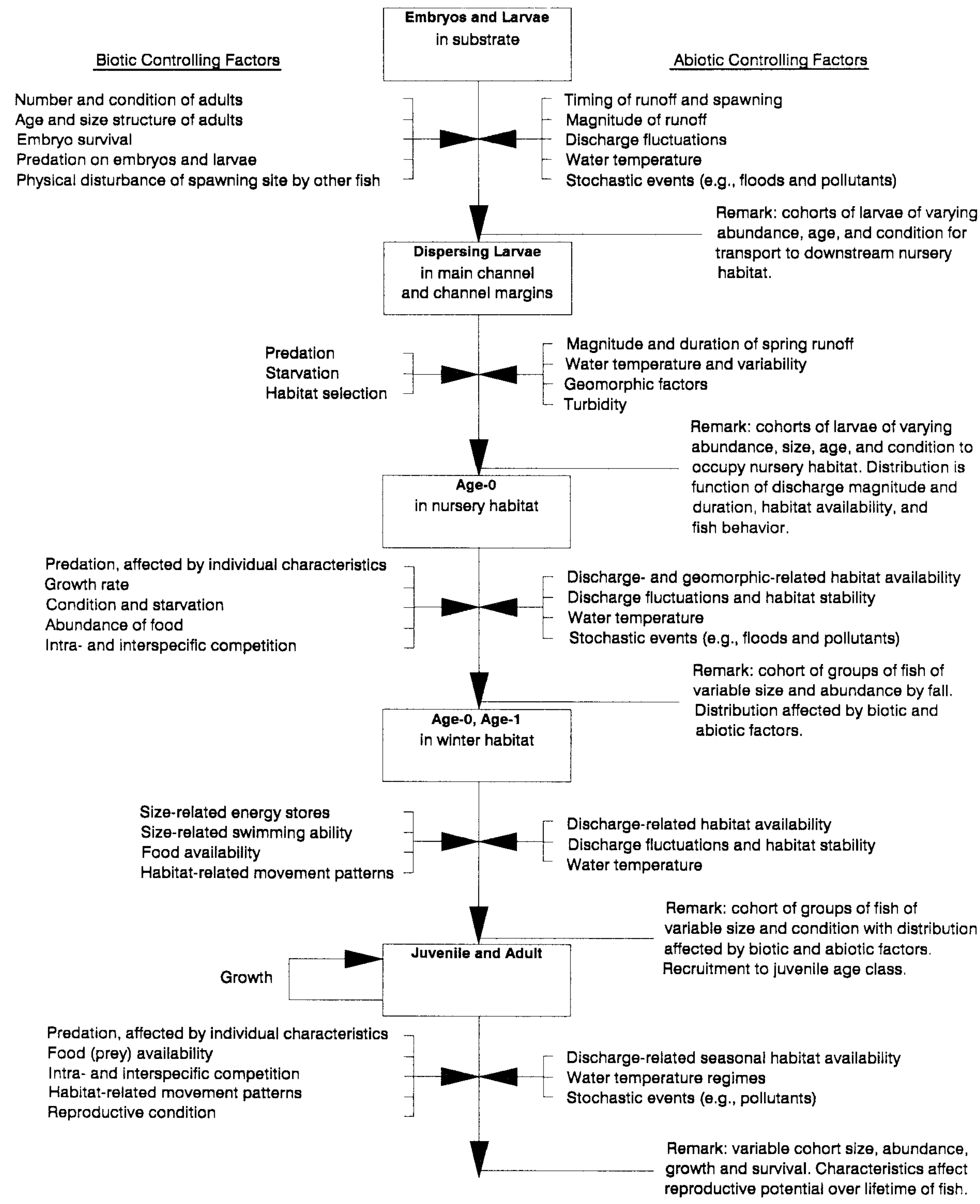


Figure 4.2.—Conceptual life-history model of Colorado pikeminnow recruitment to various developmental stages, and biotic and abiotic factors controlling recruitment. (Remarks refer to characteristics of fish that recruit to the next developmental stage.) Source: Bestgen et al. (1997)

4.2.5.2 Life History by Season

Because populations of Colorado pikeminnow are relatively abundant in comparison to other endangered fishes in the upper Colorado River basin, past research has generated considerable life-history information. Providing a comprehensive summary of recent life-history research for Colorado pikeminnow is not the purpose of this portion of the report. Instead, the goal here is to present only information that bears most directly on flow-related issues. That information is divided into calendar-year seasons of spring, summer/autumn, and winter. Even though conditions in these seasons vary among years as a result of climatic conditions, they reasonably delimit occurrence of many life-history processes, and they approximate times when different life stages of Colorado pikeminnow may shift habitat use.

4.2.5.2.1 Spring

The Colorado pikeminnow is adapted to a hydrologic cycle dominated by large spring peaks of snowmelt runoff. High spring flows reconnect floodplain and riverine habitats, a phenomenon described as the spring flood-pulse (Junk et al. 1989; Johnson et al. 1995). There is evidence that fishes in the Colorado River system respond to the flood-pulse phenomenon because juvenile and adult razorback suckers and Colorado pikeminnow are found in floodplain habitats (Holden and Crist 1981; Tyus 1990; Tyus and Karp 1990; Modde 1996). Reconnection of the river with the floodplain and subsequent inundation of detritus and vegetation allow riverine organisms to exploit rich food resources that are otherwise unavailable during most other times of the year. Additionally, floodplain habitats are typically shallower and warmer than the main channel and offer a high-growth environment for fishes (Ward 1989; Stanford et al. 1996). Spring flows also provide biological cues and drive channel-shaping geomorphic processes (Stanford 1994; Stanford et al. 1996; Poff et al. 1997).

Habitat.—Throughout most of the year, juvenile, subadult, and adult Colorado pikeminnow utilize relatively deep, low-velocity habitats that occur in nearshore areas of main river channels (Tyus 1991a). In spring, however, Colorado pikeminnow adults utilize floodplain habitats, flooded tributary mouths, flooded side canyons, and eddies that are available only during high flows (Tyus 1990). Such environments may be particularly beneficial for Colorado pikeminnow because other riverine fishes that gather in floodplain habitats to exploit food and temperature resources may serve as prey. Such low-velocity environments also may serve as resting areas for Colorado pikeminnow.

In Reach 1 of the Green River, Colorado pikeminnow historically occurred throughout the area and likely reproduced in or near Flaming Gorge Canyon. Historic floodplain habitat for all Colorado pikeminnow life stages likely occurred in Browns Park. At present, Colorado pikeminnow in Reach 1 mostly occur downstream of Browns Park in Lodore Canyon (Bestgen and Crist 2000), where deep low-velocity habitats during high flows in spring are likely to be large eddies associated with the main channel and a few flooded canyon mouths.

Most Green River floodplain habitat is currently found in Reach 2 from Jensen, Utah, downstream to the vicinity of the Ouray NWR (Section 3.6.5). Preliminary data from the Recovery Program's levee-removal evaluation project support the hypothesis that floodplain habitats are productive environments where large numbers of potential prey fishes concentrate (Crowl et al. 1998b). The importance of such habitat in spring is supported by habitat-use data summarized by Tyus and Karp (1991), the capture of large numbers of adult Colorado pikeminnow in levee-removal evaluation areas in spring 1996–1998 (Modde et al. 1998), and the collection of more than 100 adult Colorado pikeminnow in fyke nets set for razorback suckers in channel-margin eddies in 1996 and 1997. An effective capture technique for Colorado pikeminnow in the Colorado and Yampa rivers is to block backwaters and flooded tributary mouths with trammel nets in order to capture fish attempting to escape (Tyus and Karp 1989; Osmundson and Burnham 1996; T. P. Nesler, Colorado Division of Wildlife, personal communication). Such areas function similarly to flooded lowlands because they are shallow, warm, low-velocity environments where fish prey may congregate.

In canyon-bound areas such as the lower Green River in Reach 3, floodplain lowlands were historically rare. Increased vegetation encroachment, bank stability, and sediment deposition and reduced peak flow currently limit the extent of functional floodplain in that area. In Reach 3, flooded canyon mouths and washes provide most of the warm, low-velocity, off-channel habitat where large numbers of potential forage fish gather (Trammell and Chart 1999).

***Migration cues and spawning substrate preparation*.**—High spring flows also provide an important cue to prepare adults for migration, which typically commences at or just following peak spring runoff (see also summer/autumn flow needs). Other factors such as water temperature, photoperiod, and conspecific odors may also be important to cue reproduction (Nesler et al. 1988; Tyus and Karp 1989; Tyus and Karp 1991; Bestgen et al. 1998). Environmental cues used by the fish to complete their life cycle are needed in all reaches occupied by adults, including tributaries and the main-stem Green River.

High spring flows also ensure that conditions at known spawning areas in the Yampa River and in Reach 3 of the Green River are suitable for reproduction once adults arrive. Specifically, bankfull or much larger floods mobilize coarse sediment to build or reshape cobble bars, and they create side channels that Colorado pikeminnow sometimes use for spawning (Harvey et al. 1993; J. O'Brien, FLO Engineering, Inc., personal communication). Spring flows greater than 244 m^3/s in Lodore Canyon of Reach 1 result in significant channel maintenance (Martin et al. 1998) and may rework and rebuild potential spawning habitat for adult Colorado pikeminnow.

***Spring sediment transport to prepare summer backwater habitat*.**—Backwaters and the physical factors that create them are vital to successful recruitment of early life stages of Colorado pikeminnow. Occasional very high spring flows are needed to transport sediment and maintain or increase channel complexity. During high-flow events, the elevations of sandbars increase, and if high flows persist through summer, few backwaters are formed (Tyus and Haines 1991). Post-runoff low flows sculpt and erode sandbars and create complex backwater habitat critical for early life stages of all native fishes, particularly Colorado pikeminnow. Deeper, chute-channel backwaters are preferred by age-0 Colorado pikeminnow in Reaches 2 and 3 of the Green River (Tyus and Haines 1991; Day et al. 1999, 2000; Trammell and Chart 1999).

Past research indicated that a single flow level may optimize backwater habitat availability in Reach 2 for age-0 Colorado pikeminnow (Pucherelli et al. 1990; Tyus and Haines 1991; Tyus and Karp 1991). However, geomorphic processes are dynamic and driven by the level of spring flows, the frequency of large floods, and post-peak flows (Bell et al. 1998; Rakowski and Schmidt 1999; Chapter 3 of this document). Consequently, flows to achieve optimum backwater availability may be different each year and depend on year-to-year bar topography (Rakowski and Schmidt 1999).

***Reduction of nonnative fishes*.—**A collateral benefit of occasional very high spring or summer flows may be temporary reduction of populations of nonnative fishes (Section 4.1.2). Short-term reductions in the abundance of nonnative fishes may provide a window of time during which the survival of early life stages of Colorado pikeminnow is enhanced. For example, results of individual-based model simulations and field data suggest that mid-summer reductions in the abundance of nonnative fishes such as red shiner as a result of spawning mortality may enhance recruitment of Colorado pikeminnow (Bestgen 1997; Bestgen et al. 1997). Existing information suggests that the effects of high flows may be particularly beneficial in canyon reaches. More comprehensive data are needed from all river reaches before definitive conclusions can be made about effects of high spring flows on nonnative fishes.

4.2.5.2.2 Summer and Autumn

Abundance and survival rates of early life stages of many fishes often define rates of adult recruitment (Houde 1987). For Colorado pikeminnow, many of those critical processes are related to reproduction and to factors that affect the growth and survival of early life stages in summer and autumn.

***Reproduction*.—**There are two major spawning locations for Colorado pikeminnow in the Green River system: Gray Canyon in Reach 3 of the Green River and Yampa Canyon in the lower Yampa River. Another spawning area may occur in Desolation Canyon, as indicated by adult movement patterns reported by Irving and Modde (2000) and the presence of ripe fish (M. A. Trammell, Utah Division of Wildlife Resources, personal communication), but the location and importance of this area has not been verified. The lower Yampa River spawning area is included in this discussion because it has been well-studied and is located near Reach 1 of the Green River, where ripe and presumably reproducing adults historically occurred (Vanicek et al. 1970). Another reason to include the lower Yampa River area in this discussion is because spawning adults converge on this site from all areas of the system, including the main-stem Green River.

Because adult Colorado pikeminnow converge on spawning areas from throughout the Green River system to reproduce at only two known localities, migration cues are an important part of the reproductive life history. In general, adults begin migrating in late spring or early summer.

Migrations begin earlier in low-flow years and later in high-flow years (Tyus and Karp 1989; Tyus 1990; Irving and Modde 2000). Migrations to the Yampa River spawning area occur coincident with, and up to 4 weeks after, peak spring runoff, when water temperatures are usually 14–16°C (Tyus 1990; Irving and Modde 2000). Rates of movement for individuals are not precisely known, but two individuals made the more than 400-km migration from the White River below Taylor Draw Dam to the Yampa River spawning area in less than 2 weeks (Irving and Modde 2000). Photoperiod may also play a role, since day length increases and is near annual maximum when Colorado pikeminnow usually migrate (Tyus 1990). Reproduction generally begins earlier in the lower Green River than in the Yampa River (Bestgen et al. 1998). Earlier reproduction in the Green River could be a result of the earlier migration and arrival of adults at the spawning area in Gray Canyon, a shorter migration distance, and warmer water temperatures that promote the maturation of gametes.

Although direct observation of Colorado pikeminnow spawning was not possible because of high turbidity, radiotelemetry indicated spawning occurred over cobble-bottomed riffles (Tyus 1990). The adhesive eggs require clean cobble surfaces for secure attachment (Hamman 1981; Tyus and Karp 1989). Post-peak summer flows are important because they create and maintain sediment-free interstices in the cobble substrate; sedimentation of the spawning substrate can suffocate embryos.

The mechanism for spawning-bar construction and maintenance in the Yampa River has been studied (Harvey et al. 1993; Chapter 3 of this document). High flows that occur before spawning transport unsorted sediments to depositional areas of the channel created by a large backwater. As flow decreases, the downstream backwater disappears, which increases the local hydraulic gradient. Subsequent dissection of the deposit by chute channels enhances removal of fines (Harvey et al. 1993; J. O'Brien, FLO Engineering, Inc., personal communication) and results in loose, clean cobble over which fertilized eggs are deposited.

The timing of migrations and associated environmental conditions noted in telemetry studies was mostly verified by otolith aging of larvae captured in drift nets downstream of spawning areas. In the lower Yampa River from 1990 to 1996, the date for first reproduction ranged from 13 June to 1 July. These dates were 5–41 d after maximum spring runoff and occurred when water temperatures were 16.0–18.6°C. The temperatures at initiation of reproduction reported by Bestgen et al. (1998) were relatively low when compared with the temperatures reported in most other accounts (Haynes et al. 1984; Tyus 1990), although Nesler et al. (1988) did note reproduction at water temperatures as low as 16°C. Bestgen et al. (1998) used otolith-increment counts to age larvae (Bestgen and Bundy 1998) captured just downstream of spawning areas, which is a more accurate technique for estimating spawning periods than are captures of ripe fish. The first peak in reproduction, which was qualitatively defined as a notable increase in capture rates of larvae relative to the number caught throughout the summer, generally occurred 3–9 d after the onset of spawning and usually when mean daily water temperature exceeded 18°C for 2–15 d. Water temperature in the relatively high-flow year of 1993 was 16.3°C when the first peak in reproduction was noted.

In the lower Green River during 1991–1996, the date of first reproduction typically ranged from 9 to 24 June. The relatively late date of 20 July in 1995 was likely caused by an inability to capture larvae in that high-flow year (Bestgen et al. 1998). The first reproduction was 12–32 d after peak runoff and occurred when water temperatures were 19.8–23.0ºC, although Bestgen et al. (1998) suggested that those temperatures may be incorrect. The first peak in reproduction generally occurred 0–9 d after the onset of spawning and after the mean daily water temperature exceeded 18ºC for 22–45 d.

Laboratory studies suggested that wild embryos may incubate in the spawning substrate for 4–7 d, with duration inversely related to water temperature (Hamman 1981; Marsh 1985; Bestgen and Williams 1994). Temperatures from 18 to 26ºC produced similar and relatively high rates of hatching (54–79%) and survival to 7 d posthatch (52–88%). Survival was only 13% at 30ºC, which may be near the upper lethal limit for embryos. Hatching success at 16ºC, the lowest temperature at which Colorado pikeminnow were known to spawn in the wild (Bestgen et al. 1998), is unknown. Hatching success averaged about 10% higher in fluctuating temperatures (5ºC diel range) than in constant temperatures (18 to 26ºC). The main channel of the unregulated Yampa River typically exhibits summer temperature fluctuations of at least 3 to 5ºC per day, and backwaters may fluctuate twice that much. Restoration of highly regulated river reaches to include natural diel fluctuations in temperature may enhance hatching success of native fishes.

***Drift*.—**After hatching, Colorado pikeminnow larvae develop in the substrate for 6 or 7 d. This time period is inferred from the age of most larvae collected from the Yampa and Green Rivers in drift nets set downstream of spawning areas (Bestgen et al. 1998) and assumes capture on the day of emergence. This period is consistent with the interval after hatching when larvae first attempt swim-up in the laboratory (K. R. Bestgen, personal observation). Larvae emerging from spawning substrate are entrained in swift river currents and swept downstream.

Larvae are transported downstream from spawning areas to backwaters or other low-velocity nursery habitats. Larvae from the lower Yampa River are thought to mostly colonize backwaters in alluvial valley reaches between Jensen, Utah, and the Ouray NWR (Figure 4.1). Larvae transported from the Gray Canyon spawning area drift to and inhabit backwaters in the lower portion of Reach 3. Abundance of larvae in the drift appeared to be affected by flow only during extreme years (Bestgen et al. 1998). High flow was negatively associated with abundance of larvae caught at both the Yampa River and lower Green River stations, whereas low flow was negatively associated with captures only at the Yampa River site. Low abundance during extreme years could be due to few reproducing adults, low production of larvae at spawning areas, high mortality of eggs and larvae, sampling error, or other factors (Bestgen et al. 1998).

Effects of flow regulation by Flaming Gorge Dam on reproduction and drift of Colorado pikeminnow were difficult to assess because one spawning area was in a tributary, the Yampa River, and one was far downstream in the main stem, where regulation effects are mostly attenuated (Chapter 3). Maintenance of spawning populations may depend on retaining relatively natural flow and temperature regimes, particularly in the Yampa River (Tyus and Karp 1989). Reproduction by

Colorado pikeminnow in stream reaches that are strongly influenced by regulation may be limited until more natural flow and temperature regimes are restored.

As larvae drift out of the Yampa River and into the Green River, they are exposed to cold water released from Flaming Gorge Dam. Effects of cooler water temperatures on survival of Colorado pikeminnow larvae drifting into the Green River from the Yampa River are unknown, but differences of 5–10°C between the two rivers at the confluence are common (Figure 3.13; Tyus 1991a; K. R. Bestgen, unpublished thermograph data) and may cause indirect mortality (Berry 1988). Tyus (1991a) suggested that higher recruitment of Colorado pikeminnow occurred in years when temperature differences between the two rivers were 2°C or less. Cold "shock" may induce behavioral and physiological changes and reduce swimming ability of larvae, thereby increasing their susceptibility to predation or causing moribund larvae to become stranded or buried in depositional areas (Berry 1988). Water temperature also has a strong influence on development and growth of early life stages of Colorado pikeminnow, especially when temperature is less than 22°C (Bestgen and Williams 1994; Bestgen 1996). Recognizing the negative effects of cold water temperatures on growth and development emphasizes the need to enhance the thermal regime of the Green River in Reaches 1 and 2 to reduce the effects on Colorado pikeminnow larvae drifting from the Yampa River spawning area. Reducing these effects may be especially important when flow in the Green River is high and very cold and flow in the Yampa River is lower and warm.

The exact mechanism by which Colorado pikeminnow larvae drift downstream and inhabit backwater habitat is not completely understood. The probability of larvae being carried near shorelines by prevailing river currents and eventually encountering backwaters depends on the availability of such habitat. Larvae are probably deposited in the mouths of backwaters by eddy current and may then enter the backwaters by actively swimming. Regardless of the manner in which larvae enter the backwaters, swimming in relatively swift main-channel currents uses considerable energy. Therefore, the more quickly that larvae encounter suitable backwaters, the more likely they are to survive.

Age-0 Colorado pikeminnow in backwaters.—Age-0 Colorado pikeminnow in backwaters have received much research attention (Tyus 1991b; Tyus and Haines 1991; Bestgen et al. 1997). It is important to note that these backwaters are formed after cessation of spring runoff within the active channel and are not floodplain features. Colorado pikeminnow larvae occupy these in-channel backwaters soon after hatching. They tend to occur in backwaters that are large, warm, deep, (average of about 0.3 m) and turbid (Tyus and Haines 1991). Recent research (Day et al. 1999, 2000; Trammell and Chart 1999) has confirmed these preferences and suggested that a particular type of backwater is preferred by Colorado pikeminnow larvae and juveniles. Such backwaters are created when a secondary channel is cut off at the upper end but remains connected to the river at the downstream end. These chute channels are deep and may persist even when flow levels change dramatically.

Early life stages of Colorado pikeminnow feed on a variety of small invertebrates, of which chironomids are particularly important (Muth and Snyder 1995). As it does for other fishes, the growth rate of Colorado pikeminnow depends on food abundance and water temperature (Bestgen 1996). Seasonal food abundance in Green River backwaters is most likely a function of backwater stability, nutrient levels, primary production, and “maturity,” which affects the time invertebrates have to colonize and build populations. Nance (1998) sampled planktonic invertebrates in flooded side canyons in Reach 3 during spring and early summer 1997 and found that those communities took several weeks to develop to maximum abundance levels. Benthic assemblages may be an even more important food source for early life stages of fishes in the Green River (Muth and Snyder 1995).

Nighttime temperature fluctuations may cool backwaters to well below 22°C and create suboptimal growth conditions. In a laboratory study, growth of Colorado pikeminnow larvae was optimal at 31°C and high at temperatures of 22°C or warmer (Bestgen 1996). At the highest food abundance, growth of Colorado pikeminnow larvae was 36% less at 18°C compared to growth observed at 22°C (Bestgen 1996). In the wild, early life stages of Colorado pikeminnow may move to acquire more optimal habitat. For example, Tyus (1991b) found that age-0 Colorado pikeminnow moved out of backwaters at night, presumably in response to water temperatures that were colder than the main channel, and moved back in as temperatures warmed during the day. Such a strategy would allow Colorado pikeminnow to maximize degree-day accumulation and growth in a diel period.

Reduction of main channel water temperatures in regulated river systems, such as in the upstream portion of Reach 2 in the Green River, may reduce growth of the Colorado pikeminnow that switch habitats on a diel cycle. Warmer water flowing from Reach 1 (see Section 4.2.5.4) may create a better growth environment for age-0 Colorado pikeminnow in Reach 2, especially in Echo and Island-Rainbow Parks. That portion of Reach 2 occasionally harbors early life stages of Colorado pikeminnow, particularly in summer (Tyus and Haines 1991), but their presence has not been consistently documented since the early 1970s (Vanicek and Kramer 1969; Holden and Stalnaker 1975a; Bestgen and Crist 2000).

High growth rates in the early life stages of fish are important for at least two main reasons. First, larger and faster-growing fish are more able than small-bodied fish to maintain their positions in the current and escape predators; they forage more efficiently on a wider variety of food items; and they are more likely to survive periods of low food abundance (Weatherly and Gill 1987; Bestgen 1996). Second, growth rates determine the duration of time that fish are susceptible to size-dependent predation. The abundant nonnative fishes that occur with Colorado pikeminnow in backwaters are potential predators on fish larvae. Of particular concern is the most abundant species, red shiner, a known predator on fish larvae in the wild (Ruppert et al. 1993). In laboratory tests, red shiners averaging about 60 mm TL were able to capture and consume Colorado pikeminnow as large as 22 mm TL (Bestgen et al. 1997). Larger Colorado pikeminnow were not vulnerable to red shiners because they could not be ingested.

Laboratory and mesocosm experiments and an individual-based model were used to explore effects of red shiner predation on mortality rates of Colorado pikeminnow larvae (Bestgen et al. 1997). Wading-pool experiments were used to determine rates of encounter and predation for different-sized Colorado pikeminnow prey (10–20 mm TL). Even at relatively low red shiner densities (2 fish/m^2) and under relatively realistic field conditions that included turbid water, alternative prey, and natural sand substrate, the daily predation rate on Colorado pikeminnow larvae was up to 65%. The individual-based model simulations also demonstrated that cohorts of Colorado pikeminnow with relatively fast growth rates (0.15 to 0.65 mm TL/d) survived at substantially higher rates (7 to 50%) than slow-growing fish because fast-growing fish were vulnerable to predation for a shorter period of time.

Summer flow level may also influence the quantity and quality of backwater habitat available for age-0 Colorado pikeminnow. Tyus and Haines (1991) demonstrated a negative correlation between the abundance of Colorado pikeminnow in backwaters (from fall seine samples) and flows in late summer from 1979 through 1988 (excluding 1986) in low-gradient reaches of both the lower and middle Green River. Bestgen (1997) used ISMP data collected from 1986 to 1995 and data collected by Tyus and Haines (1991) to reevaluate the effects of summer (July–August) flows on recruitment. He used a plateau model regression relationship and found that there was no relationship between summer flows and fall abundance of Colorado pikeminnow in backwaters until relatively high flows were reached. In the middle Green River, the abundance of Colorado pikeminnow was not reduced until the mean July–August flow exceeded about 155 m^3/s. However, most (5 of 8) above-average recruitment years occurred when summer flows ranged from 50 to 75 m^3/s. In the lower Green River, the abundance of Colorado pikeminnow was not affected until the mean July–August flow exceeded about 210 m^3/s. However, most (5 of 7) above-average recruitment years occurred when summer flows ranged from 53 to 110 m^3/s. From 1992 through 1996, Trammel and Chart (1999) found that backwater habitat diminished rapidly when flow exceeded 77 to 100 m^3/s, but they did not detect a significant relationship between the catch rate of pikeminnow and total backwater habitat area. Flow levels that were correlated with above-average recruitment in Reach 2 were similar to the flow level (51 m^3/s) that was thought to optimize backwater habitat in 1987 in that reach (Pucherelli et al. 1990; Tyus and Karp 1991).

Water-level fluctuations from either natural causes or hydropower production can cause drying or flow-through conditions that force fish to move from low-velocity backwater habitat to the energetically expensive, higher-velocity and cold main channels. Fluctuations also may flush nutrients and potential fish foods from the backwater, disrupt and cool temperature regimes, reduce the abundance of important benthic chironomid assemblages, and cause stranding and death of fish if individuals are trapped in isolated pools. Blinn et al. (1995) found that invertebrate assemblages in channel-margin habitats of the Colorado River were reduced by 85% by a single 12-h desiccation event.

Increased flow may also be caused by precipitation from summer thunderstorms. In Reach 3 of the Green River, Bestgen (1997) found reduced growth and low survival of cohorts of wild Colorado pikeminnow whose hatching dates were concurrent with storm-caused high flows in 1991 and 1992. Availability of backwater habitat was reduced during those high-flow events (Trammell and Chart 1999; K. R. Bestgen, personal observation) and may have been the reason for poor growth and survival of Colorado pikeminnow. Also, slow growth likely extended the period of susceptibility to predation (Bestgen et al. 1997), which may have further reduced survival. Effects of short-term increases in flow caused by thunderstorms may be similar to effects of shorter-term but more regular fluctuations caused by hydropower production, because each can upset the thermal regime, food availability, stability, and availability of backwaters.

In summary, an optimal river-reach environment for growth of early life stages of Colorado pikeminnow has warm, nonfluctuating backwaters, warm river channels, and abundant food: conditions associated with the historic hydrograph. The habitat presently available imposes daily fluctuating environments and lower water temperatures that are likely to produce lower rates of fish growth and survival. Loss of backwater food-web function was considered a major impediment to restoration of native fishes in hydropower-regulated rivers (Stanford 1994; Stanford et al. 1996).

The flow and stage needed to optimize backwater habitat quantity, quality, and stability for early life stages of Colorado pikeminnow in Reaches 2 and 3 vary each year depending on antecedent flows and other factors (Chapter 3). This process may be most important in Reach 2, because no early life stages of Colorado pikeminnow presently occur in Reach 1, and fluctuations caused by daily operation of Flaming Gorge Dam are mostly attenuated in Reach 3. Backwaters occupied by Colorado pikeminnow in Reach 2 have an average depth of about 0.3 m (Tyus and Haines 1991; Day et al. 1999, 2000), and may be susceptible to even minor fluctuations in stage. Under flows recommended in the 1992 Biological Opinion (Chapter 1), backwater habitats at Jensen may fluctuate up to 11 cm (Yin et al. 1995). This condition suggests that a portion of the backwater area may be desiccated during each fluctuation event. A worst-case scenario in summer may occur when the Yampa River is low, as it was in 1994. By August of that year, releases from Flaming Gorge Dam made up more than 90% of the Green River flow at Jensen, and stage changes of more than 15 cm occurred there (K. R. Bestgen, personal observation). These fluctuating releases may have dewatered substantial portions of backwater habitats daily.

There may also be a nonlinear relationship between river stage and backwater habitat availability. In Green River Reach 2, Pucherelli et al. (1990) found backwater area increased 47% in Island Park and 37% near Jensen when flow was reduced by only 2% from 46 to 45 m^3/s. Although there is likely some error associated with measurement of backwater area, flow changes for power production are much greater than 2% and may substantially alter backwater habitat during most low-flow periods.

Relatively stable, high-quality backwaters are an essential feature of age-0 fish habitat through autumn and this habitat type is rare, particularly in high-flow years when water is cool in summer (e.g., 1982–1984; Tyus and Haines 1991; Bestgen 1997). In cool water years, Colorado pikeminnow spawn later (Bestgen et al. 1998), and young would require an extended growth period in autumn to reach a size that would enhance overwinter survival (see Section 4.3; Converse et al. 1999; Haines et al. 1998). Continued growth late into the year may also be important because of continued size-dependent predation from nonnative fishes.

4.2.5.2.3 Winter

During the pre-regulation period, winter flows in the Green River were generally low and relatively stable (Table 3.8), which created stable habitat for biota (Wick and Hawkins 1989). Winter is also the season when stress on aquatic organisms can be high, because of freezing conditions, diminished habitat, formation of frazil ice, depletion of nutritional reserves, low food-conversion rates, and low metabolic efficiency. All of these factors may reduce the condition and survival rate of fishes (Toneys and Coble 1979; references in Thompson et al. 1991; Valdez 1995). Habitat availability affects overwinter survival of fish in streams where winter conditions are harsh (Cunjak and Power 1987; Reynolds 1997). Of particular importance may be availability of low-velocity resting habitats, where fish can feed and conserve energy (Wick and Hawkins 1989; Thompson et al. 1991).

Effects of winter conditions on Colorado pikeminnow in the Green River system are less completely understood than those of other seasons because of the difficulty of obtaining reliable field data. Winter studies have principally focused on overwinter survival of age-0 Colorado pikeminnow (Thompson et al. 1991; Converse et al. 1999; Haines et al. 1998) or on habitat use and movement of adult Colorado pikeminnow in the regulated Green River (Valdez and Masslich 1989; Valdez 1995) or in the Yampa River (Wick and Hawkins 1989). Other winter studies focused on ice processes in the Green River (Valdez 1995; Hayse et al. 2000).

Age-0 Colorado pikeminnow are known to occupy backwaters in late autumn and early spring (Tyus and Haines 1991; Trammel and Chart 1999) and probably occur in backwaters in winter under ice, although this has not been observed. Wick and Hawkins (1989) studied the thermal and physical stability of backwater habitat used by adult Colorado pikeminnow through winter in the Yampa River and found dissolved-oxygen levels well above saturation, indicating some primary productivity. Food organisms such as aquatic invertebrates and small-bodied fishes were also present. Stable, productive, low-velocity conditions that promote energy conservation and survival in age-0 Colorado pikeminnow are likely important features of overwintering habitat.

Energy reserves, particularly lipids, are thought to influence overwinter survival of age-0 fish (see Thompson et al. 1991 for a review). Because lipid stores are generally positively correlated with body size and condition of fish, biotic and abiotic conditions in summer and autumn that affect growth may influence overwinter survival. Thompson et al. (1991) found that smaller Colorado pikeminnow with lower amounts of lipid were in poorer condition and survived at lower rates than larger fish over a simulated winter period in the laboratory, and they concluded that overwinter survival of wild fish may be size-dependent.

Comparison of catch-effort data collected in fall and then again in spring from 1979 to 1988 showed negligible overwinter mortality of age-0 Colorado pikeminnow relative to other seasons (Tyus and Haines 1991). However, other studies in other years (Converse et al. 1999) or those using capture-recapture estimation techniques (Haines et al. 1998) have demonstrated substantial overwinter mortality, especially for small-bodied Colorado pikeminnow. Converse et al. (1999)

suggested that size-dependent overwinter mortality was important in some years, but in others, the abundance of Colorado pikeminnow in spring was mostly a function of autumn abundance. Haines et al. (1998) reported overwinter survival of 56 to 62 % when fish were relatively large. In another year when fish were relatively small, overwinter survival was only 6%. They suggested that small fish may have lacked sufficient energy reserves in that high-flow year to survive.

Fish size and body condition in winter are functions of biotic and abiotic processes that occur in summer and autumn. Consequently, these factors have a strong influence on overwinter survival. An adequate supply of warm, food-rich backwaters in summer and autumn is essential for increasing the size and condition of age-0 fish prior to winter. This supply may be particularly important in years when spring runoff is high and late and reproduction is delayed into late summer (Bestgen et al. 1998). Under that scenario, fish are hatched late and have fewer days to grow. Thus, extending the growing season later into autumn may benefit such a cohort. Extending the growing season is likely most affected by maintaining flows at or below summer flow levels so that backwaters with established invertebrate communities are maintained rather than inundated by increasing flows.

Flow fluctuations, either in the presence or absence of ice, may disperse age-0 Colorado pikeminnow from backwater habitat in winter and worsen their condition and reduce their overwinter survival rate. Yin et al. (1995) suggested that stage changes of 63 cm may occur from November through January during a moderate water year under flow recommendations in the 1992 Biological Opinion. Stage changes of that magnitude may reconnect backwaters with the main channel and displace resident fishes. Given that backwaters average only about 0.3 m in depth, stage changes of twice that magnitude may de-water backwaters and trap or displace resident fishes. Fluctuations may also lead to production and accumulation of frazil ice up to 3 m thick in near shore areas, which could destroy backwaters or make them unsuitable for fish habitat (Valdez and Masslich 1989; Valdez 1995). This ice may force small fish to seek alternate low-velocity channel-margin habitat, which increases energy expenditure and likely exposes them to more sources of direct mortality. Given the preceding information, it does not seem unreasonable that relatively low flows with minimal fluctuations probably maintain the most stable backwater habitat from summer through winter.

Movement patterns and habitat use of adult Colorado pikeminnow in the Green River in winter (Valdez and Masslich 1989) and in the Yampa River (Wick and Hawkins 1989) were determined via radiotelemetry. In both rivers, Colorado pikeminnow had high fidelity to specific reaches and mostly utilized shallow, low-velocity backwaters and bar-margin eddies from December to early March (Wick and Hawkins 1989; Valdez 1995). Shallow, low-velocity habitats were used presumably to reduce energy expenditure. In the Green River, the average activity rate of adult Colorado pikeminnow under ice-free conditions increased 190% when the river stage fluctuated at rates greater than 5 cm/h (Valdez 1995). Changes in stage presumably reduced the suitability of microhabitats occupied by adults and forced them to search for other more energetically efficient locations.

Different kinds of ice cover affected fish activity rates differently (Valdez 1995). Movement rates of fish under solid surface ice were similar to those observed in ice-free, nonfluctuating conditions. Frazil ice that was unconsolidated did not alter fish movement or habitat-use patterns. However, frazil ice mixed with surface or jam-ice displaced fish from backwater and shoreline habitats to ice-free areas that were typically in the higher-velocity main channel. Fish were also forced to move away from floating ice.

The energetic and biological consequences of increased adult Colorado pikeminnow activity observed by Valdez and Masslich (1989) are unknown. However, costs of increased movement can be estimated with bioenergetics models available for other predaceous fishes. Beyers et al. (1999) used a bioenergetics model to quantify the relative importance of natural and anthropogenic stressors on fish in the natural environment. Such models may be a means to assess the potential biological consequences of energy expenditure incurred as a result of flow fluctuations or ice processes.

4.2.5.3 Recruitment Dynamics

Different life stages of Colorado pikeminnow occupy specific habitats that are distributed over a broad area in the Green River system. Adults migrate to canyon spawning areas that are generally distant from home ranges. Embryos incubate and hatch in spawning gravel. Newly emerged larvae drift downstream and into low-velocity nursery habitats. Subadults move back upstream. In alluvial valleys of the Green River where most nursery habitat occurs, age-0 and age-1 Colorado pikeminnow occupy shallow, channel-margin backwaters. Juveniles and adults eventually disperse from nursery-habitat areas and into tributaries or the main-stem Green River upstream or downstream of spawning localities (Table 4.3). Because factors that affect survival of various Colorado pikeminnow life stages are imposed over a spatially extensive area, a variety of interactions may influence recruitment success of individual year classes.

All life stages of Colorado pikeminnow in the Green River demonstrate wide variations in abundance at seasonal, annual, or longer time scales, but reasons for shifts in abundance are poorly understood. Bestgen et al. (1998) captured drifting larvae produced from the two main spawning areas in the Green River system and found order-of-magnitude differences in abundance from year to year. They reported that low- or high-flow years were often associated with poor reproduction but could not ascribe a specific cause-effect mechanism (Bestgen et al. 1998). In general, the number of age-0 fish found in the middle Green River each autumn were similar even though different-sized cohorts of larvae had been produced each previous summer in the Yampa River. An exception was the low-flow year of 1994, when the abundance of both larvae and age-0 Colorado pikeminnow was low. Conversely, the numbers of Colorado pikeminnow larvae produced in the lower Green River were similar among years, yet the abundance of age-0 fish varied in autumn. An exception was the high-flow year of 1995, when abundance of both larvae and juveniles was low.

The general lack of concordance between larval abundance in summer and age-0 abundance in autumn suggests that after some minimum number of larvae are produced, biotic and abiotic conditions in nursery habitat regulate recruitment in most years. This hypothesis is consistent with findings of Bestgen (1997) and Bestgen et al. (1997), who suggested that predation and temperature-mediated growth of Colorado pikeminnow larvae interact to affect recruitment. Specifically, predation by nonnative fishes such as red shiner may influence within-year-class recruitment of Colorado pikeminnow, because larvae that hatch early or grow slowly may be more susceptible to predation than those that hatch later or grow more rapidly. Together, these findings suggest that recruitment of age-0 fish in autumn may be regulated in most years by factors other than the number of larvae produced at spawning areas. Exceptions to this were in extreme low-flow summers when few larvae were produced (Bestgen et al. 1998) or in extreme high-flow summers when few larvae were produced and low-velocity habitat was limited (Tyus and Haines 1991).

Low recruitment of age-0 fish in autumn.—Low recruitment of age-0 fish in autumn from 1990 to 1997 noted by Bestgen et al. (1998) was further substantiated during data analyses conducted to reveal abundance trends (Figure 4.3; Bestgen 1997). Relatively high recruitment in the middle and lower Green River was noted during 1979–1982, followed by low recruitment in the high-flow years of 1983–1984, and high recruitment again during 1986–1989 (Tyus and Haines 1991). Recruitment since 1990 has been below the average of 1979–1989 period, with the exception of 1991 in the middle Green River and 1993 in the lower Green River (McAda et al. 1997; Bestgen 1997). The declining abundance of age-0 Colorado pikeminnow in the Green River system each year is opposite the pattern for adults, which appear to be increasing in abundance since ISMP sampling began in 1986 (Figure 4.3; McAda et al. 1997). Those patterns are discussed in later sections.

Many relatively small year-classes of age-0 Colorado pikeminnow have occurred in the Green River since flow recommendations of the Flaming Gorge Biological Opinion were implemented in 1992 (Tyus and Karp 1991). This situation has occurred in spite of the fact that moderate to high numbers of larvae were produced in most years (Bestgen et al. 1998). The consistently low number of age-0 Colorado pikeminnow suggests that the combination of biotic and abiotic conditions present in most of those years was not particularly beneficial with regard to Colorado pikeminnow recruitment. Reduced diel flow fluctuations from Flaming Gorge Dam and stabilized summer base flows in the Green River were two outcomes of operational changes that occurred since 1992. Because of proximity to the dam, those management actions likely affected Reach 2 the most and downstream Reach 3 to a lesser degree. The reduced abundance of age-0 fish throughout the Green River suggests that riverwide environmental factors are responsible. It may be that the relatively high flows from 1983 to 1986 altered geomorphic attributes of the Green River system, which enhanced reproductive success of adults, created extensive backwater habitat, and resulted in subsequent high abundance of age-0 Colorado pikeminnow from 1986 to 1989. However, as discussed below, production of a single abundant year-class of age-0 individuals may not be sufficient for recruitment to the adult life stage. Instead, a specific series of environmental and biotic events may need to occur in consecutive years before substantial numbers of age-1 and older Colorado pikeminnow recruit.

Recruitment of age-1 fish in autumn.—Although age-1 Colorado pikeminnow collected in spring (hatched the previous summer) were relatively abundant in backwaters before runoff

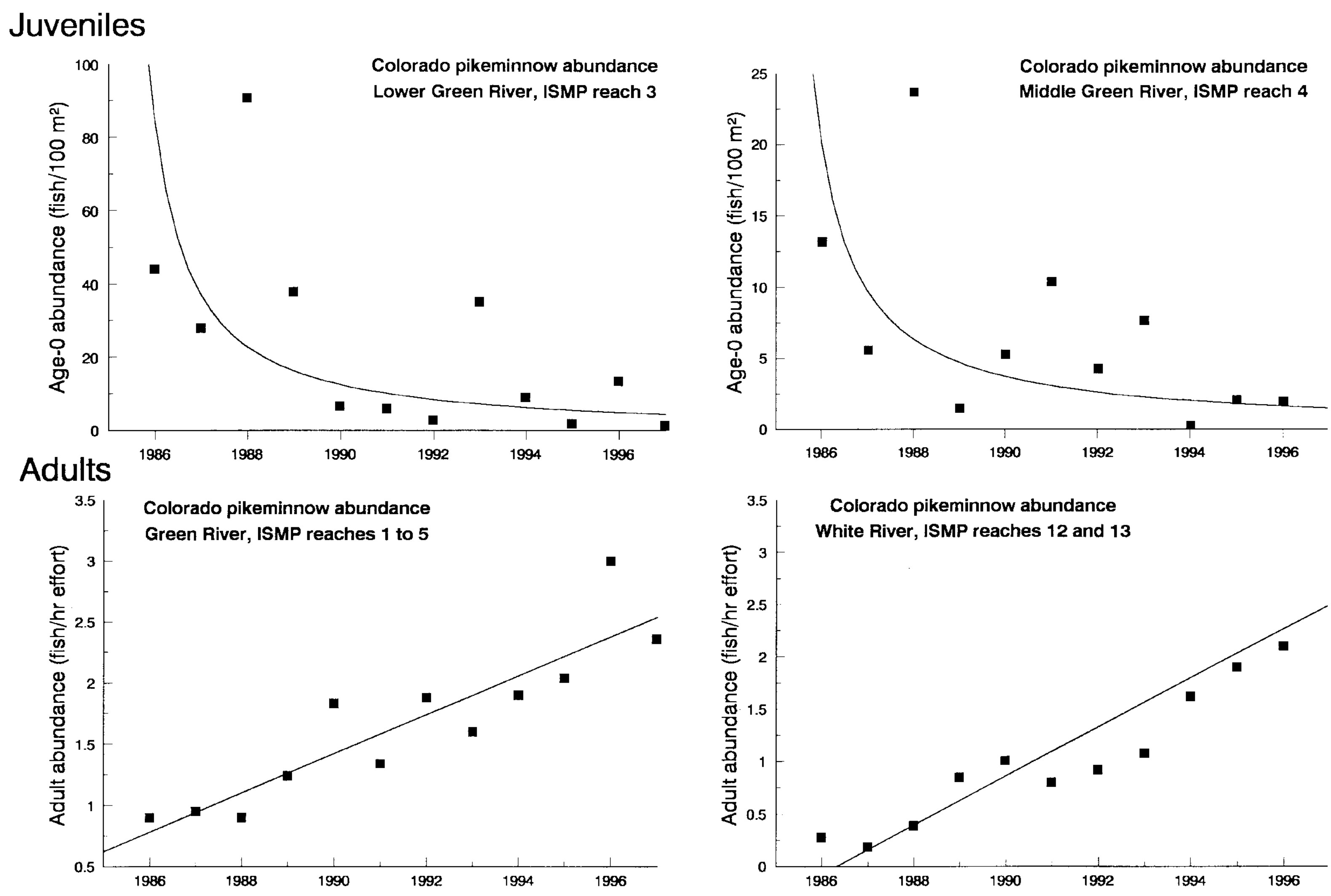


Figure 4.3—Abundance of juvenile (age-0) and adult Colorado pikeminnow in the Green River system, 1986–1997. (Juvenile abundance was measured in autumn by seining backwaters. Adult abundance was estimated from spring electrofishing, and data are presented for the main-stem Green River and the tributary the White River to illustrate a systemwide pattern.)

(Haines et al. 1998; Trammel and Chart 1999), individuals from those cohorts were rare after runoff, particularly in Reach 2 (Tyus 1991a; Haines et al. 1998). The largest concentrations of presumed age-1 fish were in Reach 3 in autumn and were particularly abundant downstream of Mineral Bottom (Tyus 1991a; McAda et al. 1994a, 1994b, 1995, 1996, 1997; Haines et al. 1998). Holden (1977) and Tyus (1991a) have suggested that the few age-1 fish captured were often found in the same backwaters as age-0 Colorado pikeminnow, but that older and larger juveniles began moving to main channel shoreline areas. Thus, one reason for the "disappearance" of juveniles may be that they were simply more difficult to capture in main channel habitat. Another reason for their low abundance may be downstream dispersal from backwater habitat during spring runoff, and higher subsequent mortality (Tyus and Haines 1991). Higher concentrations of age-1 fish in the lower Green River may be due to immigration from upstream Reach 2 or higher survival of resident fish. Each hypothesis is equally plausible but difficult to evaluate without survival estimates and fish-movement data.

The ISMP database (McAda et al. 1994a, 1994b, 1995, 1996, 1997) was analyzed with a goal to reconstruct conditions associated with particularly strong year-classes of age-1 Colorado pikeminnow in the lower Green River. Although that sampling program was mostly designed to capture age-0 Colorado pikeminnow in backwaters, larger age-1 fish have also been captured, and analysis of these data may yield insights into their abundance dynamics. An assumption is made that the number of age-1 fish captured in backwaters is an approximate index to their abundance in the system.

Colorado pikeminnow captured in ISMP sampling in autumn from 1986 to 1997 were divided into age-0 and age-1 year-classes on the basis of size. Age-0 fish were assumed to be those less than or equal to 70 mm TL, whereas those greater than 70 but less than 130 mm TL were assumed to be age-1 fish. Those size and age-classes are realistic given known and potential growth rates of age-0 fish to autumn and the subsequent spring (Tyus and Haines 1991; Bestgen 1996; Bestgen 1997; Haines et al. 1998). The density of fish in each size class was calculated by dividing the number of fish captured by the area seined. A general linear model was used to predict the abundance of age-1 fish in year n as a function of their abundance as age-0 fish the previous autumn (year $n-1$), the abundance of age-0 Colorado pikeminnow that same autumn (year n), and the highest mean daily flow during spring runoff (year n). The age-0 data were further partitioned by calculating the density of fish greater than 45 mm TL. For example, variables used to predict the abundance of age-1 fish in autumn 1997 (e.g., year n, but the year-class of 1996, year $n-1$) would be density of that same year-class in fall 1996 as age-0 fish, density of fish greater than 45 mm TL in that year-class in fall 1996, density of the 1997 year-class (age-0 fish), density of fish that were greater than 45 mm TL, and the highest mean daily flow value in spring 1997. Density of age-0 fish in year n was considered an important variable to predict the abundance of age-1 fish that same year because, on the basis of ISMP data, each age-class occupies similar habitat. Thus, biotic and abiotic factors present in the reach may affect the strength of each year class similarly, and the abundance of age-0 fish may act as a surrogate variable to predict the abundance of age-1 fish.

A general linear model ($R^2 = 0.80$) suggested that most variation in juvenile abundance was accounted for by the density of age-0 fish greater than 45 mm TL ($F = 17.88$, $P = 0.0039$, Type III SS) and by the density of fish in the same year-class as age-0 individuals greater than 45 mm TL in the previous autumn (F = 6.44, P = 0.0388, Type III SS). When spring flow was included as an independent variable, model fit increased only slightly (R^2 = 0.82; F = 0.67, P = 0.44, Type III SS). Model fit increased more (R^2 = 0.85) when the interaction term of flow*age-0 fish greater than 45 mm TL was added. The negative slope of that term suggested that high flow had a negative effect on the abundance of those large age-0 fish, probably because of a reduced growing season or lower water temperatures. Perhaps the most important conclusion drawn from these data is that in the only 3 years of strong recruitment of age-1 Colorado pikeminnow (1988, 1989, 1994), spring flow was low or very low (Figure 3.4). In the other 4 years, when flow was low but recruitment of age-1 fish was also low, abundance of age-0 fish in summer was low.

This analysis illustrates the complex and multiyear nature of the recruitment process and suggests that low spring runoff may be just one factor necessary to recruit a strong year-class of age-1 Colorado pikeminnow. It also suggests that flow management at Flaming Gorge Dam could be used to enhance recruitment of year-classes of Colorado pikeminnow in the lower Green River, if several preexisting conditions are met. For example, if an abundant age-0 year-class had high overwinter survival to spring, and flow forecasts predicted a moderate or low runoff year in the upper Green and Yampa River basins, the duration and magnitude of spring releases from Flaming Gorge Dam could be reduced to create the conditions presumed necessary for recruitment of a large year-class of age-1 Colorado pikeminnow. The precise mechanism responsible for high recruitment of age-1 Colorado pikeminnow in autumn is unknown but may be related to low dispersal of age-1 fish during runoff and favorable environmental conditions (e.g., warm water, abundant food) during summer.

Recruitment of adults.—The strong Colorado pikeminnow year-classes produced in the late 1980s and in 1993 may be responsible for the high abundance of adults currently found in the Green River system. This contention is supported by data that show the predominant size-class in most Green River Colorado pikeminnow populations that has occurred since the late 1980s is 550 mm TL, a length that might be attained only after 8–10 years of growth (Osmundson et al. 1997). Green River populations also have a concentration of smaller 300- to 350-mm TL fish (McAda et al. 1997), which may be the result of the large amount of 1993 year-class fish in the lower Green River (Figure 4.3). Data presented in McAda et al. (1997) suggest that the comparatively high present-day abundance of adults does not necessarily result in large year-classes of larvae or juveniles. Increased abundance of Colorado pikeminnow in tributary populations such as those in the White (Figure 4.3), Price, and upper Green Rivers (McAda et al. 1997; Bestgen and Crist 2000; Cavalli 1999) also may be a result of spawning and recruitment events that occurred 8–10 years ago or more.

The precise factors that contributed to large year-classes produced in both the Green and Colorado Rivers (Osmundson et al. 1997; McAda et al. 1997; this analysis) in the late 1980s are unknown. High recruitment occurred in the lower portions of both basins, which suggests that regionwide rather than river-specific factors may be responsible. It is important to note that high recruitment of age-1 Colorado pikeminnow has apparently not occurred in upstream Reaches 1 or 2 of the Green River, the areas most directly affected by Flaming Gorge Dam, during the period encompassed by ISMP sampling. This situation has not occurred in spite of the fact that age-0 fish in Reach 2 are common (Figure 4.3). Nevertheless, it is encouraging that under the right circumstances, large year-classes of Colorado pikeminnow can still be produced in this regulated system. Ongoing efforts and future management should focus on discovering the important driving variables and evaluating attempts to manage the system on the basis of this knowledge. Despite the complexity of the system, our ability to observe changes in the fish community and to manipulate environmental characteristics such as water temperature, flow regimes, ice formation, and abundance of nonnative predators holds promise for future successful management and recovery of Colorado pikeminnow.

4.2.5.4 Limiting Factors for Colorado Pikeminnow in Historic Green River Habitat

Reach 1 and the upper segment of Reach 2 historically provided habitat for some life stages of Colorado pikeminnow. It is known with near certainty that a reproducing population of Colorado pikeminnow occurred in the vicinity of Flaming Gorge Dam on the basis of the presence of ripe males (Vanicek et al. 1970). Thus, the Green River in the vicinity of Flaming Gorge Dam likely supported adult and early life stages of Colorado pikeminnow. Other researchers (Vanicek and Kramer 1969; Holden and Stalnaker 1975a) found larvae and juvenile Colorado pikeminnow common in the Green River in the lower portion of Reach 1 in Echo Park and downstream to near Jensen, Utah. Thus, it can be stated with some certainty that Reach 1 of the Green River supported nearly all life stages of Colorado pikeminnow. Dam construction and operation eliminated that population of Reach 1 adults and reduced their distribution and abundance elsewhere.

The temperature of the Green River downstream of Flaming Gorge Dam was increased moderately when penstock modifications were completed in 1978. Limited sampling effort suggested that a few adult Colorado pikeminnow inhabited the reach following penstock modification (Holden and Crist 1981; Karp and Tyus 1990a). At least two adult Colorado pikeminnow implanted with radio transmitters were recorded in Reach 1, and one was in the upper portion of Lodore Canyon (USFWS, Vernal, Utah, unpublished data). Approximately 10 angler-caught adult Colorado pikeminnow were reported from the Green River in Browns Park from 1980–1990 (H. M. Tyus, University of Colorado, personal communication).

The combined effects of warmer releases, the recent change in dam operations due to the 1992 Biological Opinion, and basinwide population increases may be responsible for re-colonization of the lower portion of Reach 1 in Lodore Canyon by adult Colorado pikeminnow. Bestgen and Crist (2000) documented a moderate-sized population of adult Colorado pikeminnow, which were present in all seasons. Individual Colorado pikeminnow up to 780 mm TL were captured, and length-mass relationships suggested fast growth and good condition of fish in that reach (Bestgen and Crist 2000). However, no evidence of reproduction by Colorado pikeminnow was noted in Reach 1. Habitat suitable for spawning may be present in the lower portion of Lodore Canyon. Thus, some of the necessary conditions for restoration of a spawning population of Colorado pikeminnow exist in the lower portion of Reach 1 in Lodore Canyon.

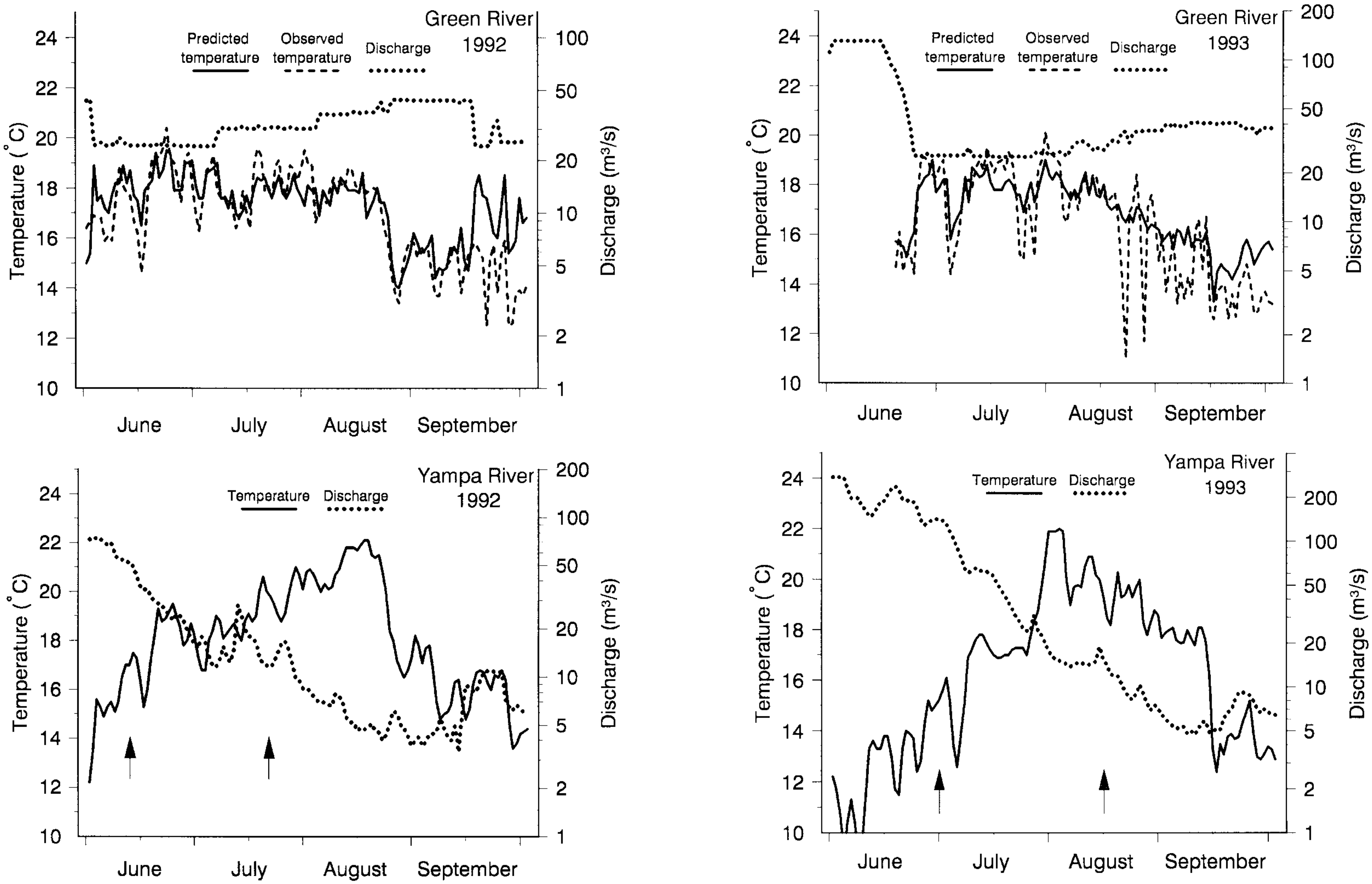
Reproduction by Colorado pikeminnow in Reach 1 may require suitable patterns of flow and temperature, similar to those in the Yampa River where reproduction occurs. A comparison of unregulated Yampa River flow and temperature regimes with those found in Reach 1 demonstrates that in most recent years, flow and temperature patterns in the regulated river were the opposite of those present where Colorado pikeminnow spawning occurs (Figure 4.4; Bestgen and Crist 2000). In the Green River from 1992 to 1996, flows declined from high spring levels to very low levels in early summer and were associated with relatively warm temperatures on the order of those needed for Colorado pikeminnow reproduction. However, flows progressively increased by mid-summer, to achieve summer flow targets prescribed by the 1992 Biological Opinion, which was contrary to natural flow patterns. Temperature modeling and field observations in Reach 1 suggest that increased flow resulted in lower temperatures later in summer (Bestgen and Crist 2000). That pattern was also the reverse of the natural regime. Reversing the trend of increased flow and decreased water temperatures in summer in Reach 1 of the Green River would be a necessary condition for Colorado pikeminnow reproduction in that reach (Bestgen and Crist 2000).

In addition to the restoration of natural flow and temperature patterns, the restoration of minimum temperature levels suitable for reproduction is necessary to restore Colorado pikeminnow in the lowermost reaches of Reach 1. Although reproduction in the Yampa River in most years started when water temperatures were relatively low, peak reproduction did not occur until temperatures exceeded 18–20^{o}C for several days and continued for several weeks. It is unlikely that reproduction of Colorado pikeminnow could be restored upstream of Lodore Canyon under any circumstances short of removal of Flaming Gorge Dam, because water temperatures would likely be too cold.

Restoration of more natural temperature patterns and levels would also enhance habitat for young Colorado pikeminnow in Reach 2 of the Green River upstream of Jensen, Utah. That area was historically a nursery habitat for early life stages of Colorado pikeminnow, but they are currently rare in that reach (Tyus and Haines 1991; Bestgen and Crist 2000). Warmer water would enhance growth and survival of that life stage and reduce the chance of temperature shock to larvae as they drift from the warm Yampa River into the relatively cool Green River (Section 4.2.5.2.2).

The recent discovery of reproducing Colorado pikeminnow in the regulated Gunnison River in Colorado (Burdick 1995) has provided an opportunity to determine the flow and temperature conditions needed to promote reproduction in that small upstream population. There, flows in spring and summer reasonably approximated historic patterns of high spring peaks and relatively low summer base flows. Temperature regimes in summer exceeded 18–20^{o}C for 2 to 5 weeks during reproduction. Similar temperature levels are recommended for Green River in Reach 1 and should be timed so that migrating Colorado pikeminnow are attracted to Lodore Canyon and resident fish remain in the reach.

Benefits of another spawning population.—An additional spawning population of Colorado pikeminnow in the Green River system would be desirable from the perspective of multiple refugia. For example, a toxic spill in the upper Yampa River could decimate both the



Discharge and temperature patterns for the unregulated Yampa River in each year are included for comparison. Arrows indicate timing of first and last spawning by Colorado pikeminnow in the Yampa River.

Figure 4.4.—Observed or predicted water temperatures for the Green River in lower Browns Park, 1992–1995. Sources: Bestgen and Crist (2000); Bestgen et al. (1998)

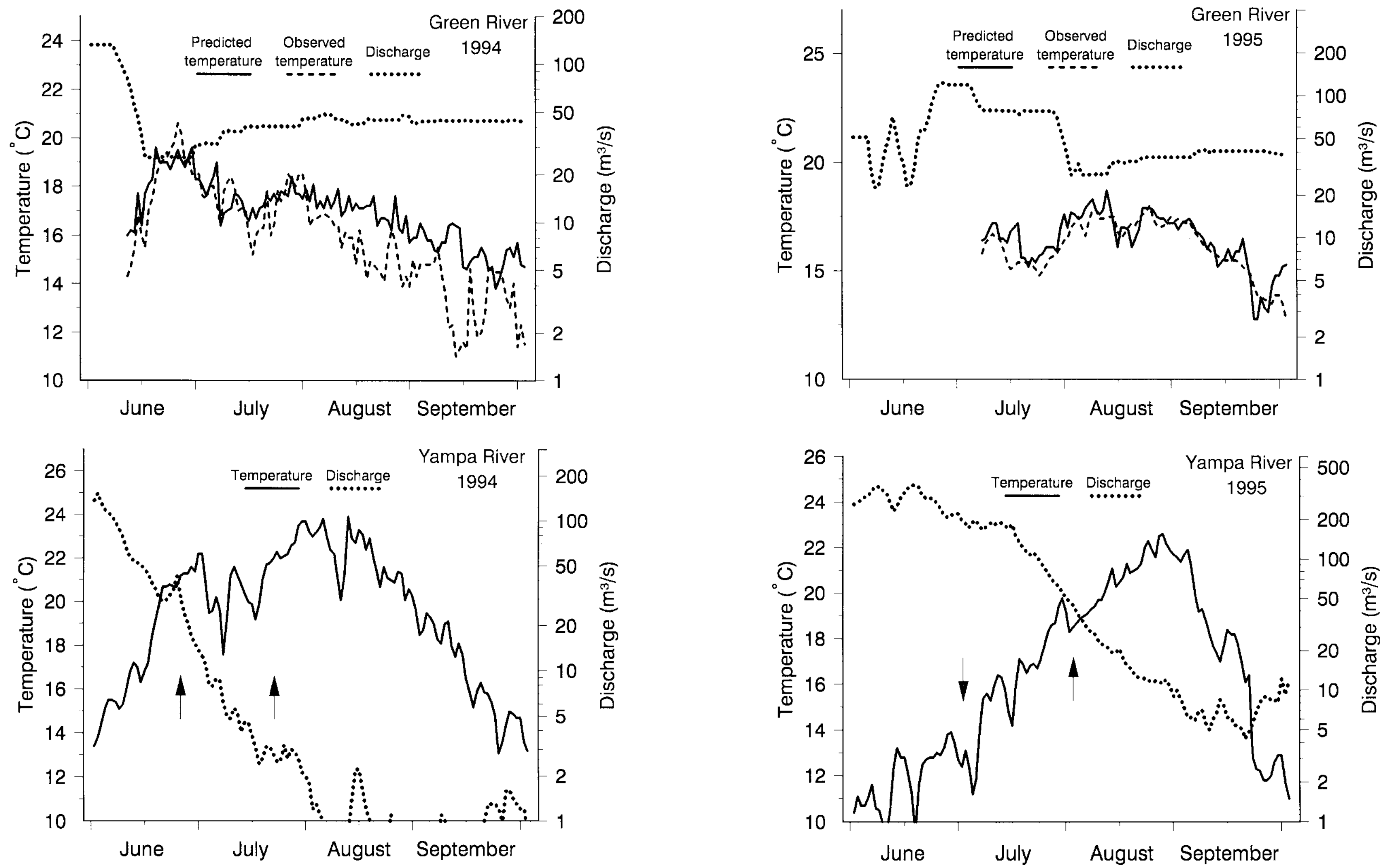


Figure 4.4.—Continued.

Yampa Canyon and Green River spawning populations if adults were concentrated in spawning areas at the time of the spill. The oil spill that occurred in the Yampa River upstream of the spawning area in summer 1989 attests to the possibility of such a scenario. Although no sampling programs were in place at the time of the spill, autumn ISMP seine sampling in downstream backwaters produced one of the lowest estimates of Colorado pikeminnow abundance during 1986–1997 (McAda et al. 1994a, 1997), presumably because of the spill. Another spawning population in a different portion of the river system would provide a safeguard for protection of the species.

4.2.6 Summary of Seasonal Flow-Habitat Relationships for Colorado Pikeminnow in the Green River System

This section focuses on the seasonality of Colorado pikeminnow life history in the context of flow-habitat relationships in the Green River system. Table 4.4 at the end of this section summarizes flow and temperature needs by season and river reach. Information taken from preceding sections is summarized here and used to make the recommendations on flow and temperatures to benefit endangered fishes in the Green River downstream of Flaming Gorge Dam (Chapter 5).

4.2.6.1 Spring

High spring flows provide a direct biological benefit to Colorado pikeminnow in at least two ways. First, high spring flows inundate floodplain habitats (Section 3.6.5) and provide warm, food-rich, off-channel habitats for juveniles, subadults, and adults. These high-quality habitats are important for growth, resting, and conditioning, particularly for adult fish that are preparing to migrate and spawn. They are especially beneficial when high-elevation snowmelt and runoff create cold and swift main channel habitats. Restricting river-floodplain interaction reduces the ecological integrity and productivity of the system and limits the growth, condition, and abundance of fishes dependent on that environment. More natural flow regimes with higher spring peaks and lower base flows, whose levels are dictated by prevailing annual hydrologic conditions, may be needed to effectively couple complex geomorphic and biological processes (Stanford 1994; Stanford et al. 1996; Poff et al. 1997). A second biological benefit of high spring flows is to provide cues for initiation of spawning migrations and spawning readiness.

High spring flows also serve important fluvial geomorphologic functions that prepare summer habitat for early life stages of Colorado pikeminnow. Siltation of spawning substrate and suffocation of sensitive, nonmobile embryos are among the most pervasive problems in aquatic ecosystems (Waters 1995) and may be a factor that determines recruitment success of Colorado pikeminnow. Spring flows rework in-channel substrate, which removes silt deposits (Section 3.6.3). High spring flows also transport sediment, build sand-bar complexes, and create chute channels that eventually become the preferred backwater habitat of early life stages. Processes that create sandbars and sculpt and erode them into usable habitat are complex, and flows that maximize such habitats are season- or year-specific. High spring flows also remove encroaching riparian vegetation, which may increase shoreline complexity and habitat diversity. Low-velocity habitat is mostly lacking when flows are less than bankfull but higher than the elevation of in-channel sand bars. Because of that, maintenance of flows at those levels for extended periods via dam releases (e.g., 1994) should be avoided.

Occasional low spring flows also may benefit recruitment of Colorado pikeminnow. The recruitment dynamics assessment (Section 4.2.5.3) suggested that high recruitment of age-1 Colorado pikeminnow in autumn occurred only under a specific set of conditions. High recruitment may require production of a large year-class of Colorado pikeminnow with a relatively large body size the year before, high overwinter survival followed by relatively low spring runoff, and conditions that promote high growth and abundance of the age-0 year-class. Biological monitoring data and flow forecasts could be used to identify years when management of Flaming Gorge Dam flows may enhance recruitment of year-classes of Colorado pikeminnow in the lower Green River.

4.2.6.2 Summer and Autumn

Summer and autumn are critical periods in the life history of Colorado pikeminnow because important processes such as reproduction and growth of larvae occur then. Early in this period, high flow is important for maintaining clean cobble substrate at spawning sites. Declining flow and increasing water temperature may be important reproductive cues for adult Colorado pikeminnow that are migrating to or are at spawning areas. Adult Colorado pikeminnow generally begin spawning when temperatures reach 16–18°C, and spawning peaks with warmer temperatures. Providing flows and temperatures in the lower portion of Reach 1 of the Green River that are more similar to those in the Yampa River may promote establishment of a reproducing population of Colorado pikeminnow in Reach 1. To accomplish this, flows and release temperatures should be managed to achieve temperatures of 18–20°C for 2–5 weeks in the downstream portion of Reach 1.

Following spawning, embryos and larvae develop at rates that are temperature dependent. However, hatching and survival rates to 7 d posthatching are similar at temperatures from 18 to 26°C. Larvae typically emerge from spawning substrate when they are 6 to 9 d old but may emerge sooner if stressed by high-turbidity conditions. Larvae are transported to downstream nursery habitat within 1 to 2 d, except at very low flow.

Downstream transport of larvae from the Yampa River into the Green River may result in indirect mortality in some years because of temperature differences between the two rivers. The likelihood of this happening is greatest when flows from the Green River are high and cold in the summer and flows from the Yampa River are low and warm. Temperature differences in the two rivers have approached 10°C at times (e.g., summer 1998), a level which may cause larvae to lose equilibrium. Larvae in that condition would have reduced or no swimming ability and presumably increased susceptibility to predation, or they might suffocate if covered in bottom sediments. Effects of cold shock may be partially responsible for the extremely low recruitment of age-0 Colorado pikeminnow in some years. Thus, minimizing the difference between water temperatures in the

Green and Yampa Rivers at their confluence so that the Green River is no more than about 5°C colder than the Yampa River, perhaps through management of flow and release temperatures, could enhance the growth and survival of Colorado pikeminnow (Section 4.2.5.2.2). Enhancing water temperatures in Reach 1 also may restore the thermal environment of Reach 2 backwater habitats in Echo Park and Island-Rainbow Parks for Colorado pikeminnow early life stages.

Flow levels in summer and autumn influence the formation and maintenance of backwater habitat in nursery reaches. High spring flows build sand bars, but lower summer flows sculpt them and create backwater habitat that is used by early life stages of Colorado pikeminnow. Rapid reductions in flows in summer allow backwaters to form sooner, which may promote earlier colonization by invertebrates. The ideal environment for Colorado pikeminnow larvae for a summer-autumn period would be a reach that has deep and relatively stable backwaters with abundant invertebrate forage and where main-channel and backwater temperatures equal or exceed 22°C. Chute-channel backwaters apparently preferred by Colorado pikeminnow are relatively deep and may be particularly valuable because the invertebrate and fish assemblages they support are less affected by flow fluctuations. Fast growth rates and larger body size are particularly important when size-dependent processes such as predation affect recruitment of early life stages. Maintenance of relatively stable, warm, food-rich backwaters through autumn is important to maintain high growth rates and enhance the size of Colorado pikeminnow prior to winter.

4.2.6.3 Winter

Winter is generally considered a stressful time for fishes in streams because of the lack of suitable overwinter habitat and many other factors. In the unregulated Yampa River, flows are low and steady, and habitat is stable. Adults utilize small river reaches and low-velocity habitat (e.g., backwaters), which presumably minimize energy expenditure and provide refugia.

In the regulated Green River, age-0 Colorado pikeminnow occupy nearshore backwaters in ice-free conditions and presumably occupy the same habitat under ice. Low flows that are similar to those that occurred in summer and autumn may maximize backwater habitat availability and fish survival. Higher flows or fluctuating-flows reduce backwater stability and may force fish to move and find new backwaters where food resources may be limited.

Increased fish movement and reduced availability of habitat and food resources likely reduce the condition of age-0 Colorado pikeminnow in winter. Movement also may cause higher levels of direct mortality because of increased predation, risk of abrasion from substrate and frazil ice, and exposure to super-cooled water. A reduction in flows and reduced flow fluctuations, especially in years when age-0 fish are relatively small (e.g., < 40 mm TL), may enhance the condition and survival of age-0 fish.

In the regulated Green River, when compared with the unregulated Yampa River, flow fluctuations and associated ice processes increased movement and energy expenditure by adult

Colorado pikeminnow. Although the biological consequences of increased movement are unknown, high rates of activity worsen a fish's condition in winter and cause it to reallocate its energy reserves, which might otherwise be used for migration and reproduction. Relatively low flows and reduced flow fluctuations may benefit both age-0 and adult Colorado pikeminnow in winter.

Table 4.4.—Summary of flow and temperature needs of Colorado pikeminnow in the Green River system, Utah and Colorado.

Season	River Reach[a]		
	1	2	3
Spring	● Onset of releases from Flaming Gorge Dam closely coordinated with forecasts of spring-runoff flows for the Yampa River (timed to supplement Yampa River peak and immediate post-peak flows) to provide flows compatible with requirements in downstream reaches. ● Occasional high flows (> 244 m^3/s) to disturb encroaching floodplain vegetation, increase habitat complexity, remobilize floodplain substrate, and rejuvenate in-channel substrates that may be suitable for spawning by Colorado pikeminnow. ● Releases that decline in late spring or early summer in a pattern that simulates a natural hydrograph to provide cues to attract migrating adults, to cue resident adults to spawn in Lodore Canyon, or to motivate resident fish to migrate and spawn elsewhere. ● Releases that provide more natural temperature levels and patterns to attract migrating adults and to aid gonadal maturation in resident adults that may spawn in Lodore Canyon.	● Increasing flows associated with the beginning of spring runoff to cue fish for the upcoming early summer migration to spawning areas. ● Inundation of floodplain habitats in the Jensen and Ouray areas to provide warm, food-rich environments for growth and conditioning of all life stages and gonadal maturation in adults, and to reestablish river-floodplain connections for restoration of the ecosystem. – Overbank flooding with existing levees: flows greater than 527 m^3/s. ● Flows greater than 100 m^3/s flood off-channel habitats (e.g., tributary mouths and side canals and channels) in the Jensen and Ouray areas (see Section 4.3.6). ● Flows that scour sediment from substrate in potential spawning areas. ● Flows that transport sediment and build in-channel sand bars for backwater habitats for age-0 fish during summer. Occasional high flows needed to build high sand bars, scour encroaching vegetation, and maintain habitat complexity.	● Increasing flows associated with the beginning of spring runoff to cue fish for the upcoming early-summer migration to spawning areas. ● Inundation of floodplain habitats to provide warm, food-rich environments for growth and conditioning of all life stages and gonadal maturation in adults, and to reestablish river-floodplain connections for restoration of the ecosystem. – Overbank flooding with existing levees between the White River and upper end of Desolation Canyon: flows greater than 623 m^3/s. – Overbank flooding with existing levees in Canyonlands National Park: flows greater than 1,100 m^3/s. ● Flows greater than 200 m^3/s flood off-channel habitats (e.g., tributary mouths, washes, and side canyons) in the Millard Canyon and Anderson Bottom areas in Canyonlands National Park (see Section 4.3.6). ● Flows that scour sediment and rework substrate in spawning areas in Desolation and Gray Canyons.

Table 4.4.—Continued.

Season	River Reach[a]		
	1	2	3
Spring (Cont.)		● Occasional high flows to reduce the abundance of nonnative fishes in low-velocity habitats. ● Lower spring releases in drier years may benefit survival and recruitment of abundant spring year-classes of age-1 fish in the following autumn.	● Flows that transport sediment and build in-channel sand bars for backwater habitats for age-0 fish during summer. Occasional high flows needed to build high sand bars, scour encroaching riparian vegetation, and maintain habitat complexity. ● Occasional high flows to reduce the abundance of nonnative fishes in low-velocity habitats. ● Lower spring releases in drier years may benefit survival and recruitment of abundant spring year-classes of age-1 fish in the following autumn.
Summer/ Autumn	● Releases that decline in late spring to mid-summer to low, relatively stable base flows in a pattern that simulates a natural hydrograph. May provide cues to attract migrating adults, cue adults to spawn in Lodore Canyon, and motivate resident fish to migrate and spawn elsewhere. Also may provide cues to post-spawning adults that are migrating back to home ranges.	● Flows that decline in late spring to mid-summer to low, relatively stable base flows. Provides cues for adults to migrate to spawning areas and for post-spawning adults that are migrating back to home ranges. Timing and flow level depends on the annual hydrologic condition. Reduces the length of time between end of overbank flooding and start of in-channel backwater development (period when availability of in-channel low-velocity habitats is limited) and permits earlier colonization of backwaters by invertebrates upon which early life stages depend.	● Flows that decline in late spring to mid-summer to low, relatively stable base flows. Provides cues for adults to migrate to spawning areas and for post-spawning adults that are migrating back to home ranges. Reduces the length of time between end of overbank flooding and start of in-channel backwater development (period when availability of in-channel low-velocity habitat is limited) and permits earlier colonization of backwaters by invertebrates upon which early life stages depend.

Table 4.4.—Continued.

Season	River Reach[a]		
	1	2	3
Summer/ Autumn (Cont.)	● Releases that provide more natural temperature levels and patterns to attract and retain migrating adults, and to aid gonadal maturation and growth of resident adults that may spawn in Lodore Canyon. Mean daily temperatures that exceed 18 to 20ºC for a period of 2 to 5 weeks in mid-summer in upper Lodore Canyon are the minimal levels and durations needed.	● Flows that provide more natural temperature levels and patterns to provide cues for adults migrating to spawning areas, to aid gonadal maturation, and to aid growth of early life stages in nursery habitats, including those in Echo and Island-Rainbow parks. Temperature of the Green River should be no more than about 5ºC lower than the Yampa River at their confluence to enhance survival of drifting early life stages. ● Relatively low flows that maximize in-channel backwater habitats for age-0 and juvenile fish. Most years with above average age-0 recruitment occurred with mean July–August flows of 50 to 75 m^3/s as measured at the Jensen gage. ● Flows that provide for relatively stable backwater nursery habitats to reduce dispersal from backwaters and to enhance invertebrate productivity and growth and survival of early life stages of Colorado pikeminnow.	● Relatively stable and low flows that maximize in-channel backwater habitats for age-0 and juvenile fish. Most years of above average age-0 recruitment occurred at flows of 53 to 110 m^3/s. From 1992 through 1996, backwater habitat diminished rapidly when flow exceeded 77 to 100 m^3/s. ● Flows that provide for relatively stable backwater nursery habitats to reduce dispersal from backwaters and to enhance invertebrate productivity and growth and survival of early life stages of Colorado pikeminnow.
Winter	● Releases from Flaming Gorge Dam to provide flows compatible with requirements in downstream reaches.	● Low, relatively stable flows to reduce the likelihood of increased movements of adults caused by ice breakup and transport. Also may reduce disruption of near-shore low-velocity habitats.	● Low, relatively stable flows to reduce likelihood of increased movements of adults.

Table 4.4.—Continued.

Season	River Reach[a]		
	1	2	3
Winter (Cont.)		● Flows at levels similar to autumn in order to provide relatively stable backwater habitats may reduce the likelihood of movement by early life stages of Colorado pikeminnow and may increase overwinter survival.	● Flows at levels similar to autumn in order to provide relatively stable backwater habitats may reduce the likelihood of movement by early life stages of Colorado pikeminnow and may increase overwinter survival.

[a] River reaches: (1) Flaming Gorge Dam to Yampa River confluence, (2) Yampa River confluence to White River confluence, and (3) White River confluence to Colorado River confluence.

4.3 RAZORBACK SUCKER

4.3.1 Distribution and Status Overview

The endangered razorback sucker is a monotypic, endemic catostomid of the Colorado River basin (Miller 1959; Minckley et al. 1986) and was once widely distributed in warm-water reaches of larger rivers from Mexico to Wyoming (Jordan and Evermann 1896; Minckley 1973; Behnke and Benson 1983; Bestgen 1990; USFWS 1994). Historic records indicate that the lower basin (Figure 1.1) supported the largest numbers of razorback sucker; the species was most abundant in the main-stem Colorado River downstream of present-day Lake Mead, the Salton Sea area, and the lower Gila River drainage in Arizona (Kirsch 1888; Gilbert and Scofield 1898; Minckley 1973, 1983; Bestgen 1990; Minckley et al. 1991a). In the upper basin, razorback suckers historically occurred in the Colorado, Green, and San Juan River drainages but apparently were common only in calm, flat-water reaches of the main-stem Colorado and Green Rivers and lower portions of their major tributaries (Jordan 1891; Evermann and Rutter 1895; Ellis 1914; Simon 1946; Hubbs and Miller 1953; Koster 1960; Sigler and Miller 1963; Baxter and Simon 1970; Vanicek et al. 1970; Holden and Stalnaker 1975a, 1975b; Wiltzius 1978).

Declines in the abundance and distribution of razorback suckers were first noted in the early 1940s (Dill 1944; Wiltzius 1978). Today, the species is one of the most imperiled fishes in the Colorado River basin and exists naturally as only a few disjunct populations or scattered individuals (Minckley et al. 1991a). Although there is evidence of reproduction in at least the larger extant populations, natural survival of fish beyond the larval period appears extremely low. Wild stocks are primarily composed of older fish and continue to decline in abundance (Lanigan and Tyus 1989; Marsh and Minckley 1989). Lack of recruitment sufficient to sustain populations has been mainly attributed to the cumulative effects of habitat loss and modification (including reductions in river-floodplain connectivity) caused by water and land development and predation on early life stages by nonnative fishes (Tyus and Karp 1990; Hawkins and Nesler 1991; Modde et al. 1995; Horn 1996; Lentsch et al. 1996b; Tyus and Saunders 1996; Hamilton 1998; USFWS 1998a).

Remaining wild populations of razorback sucker are in serious jeopardy. The largest extant population is found above Davis Dam in Lake Mohave on the lower main-stem Colorado River, Arizona-Nevada, but little or no natural recruitment has occurred since final closure of the dam in 1954 (McCarthy and Minckley 1987; Minckley et al. 1991a). Estimated numbers of adult razorback suckers in Lake Mohave declined 68% (from 73,500 to 23,000) during 1980–1993 (Marsh 1994), and further steep declines in the population are expected within the next decade (Minckley et al. 1991a; Mueller 1995). Populations of razorback sucker also occur above Hoover Dam in Lake Mead on the lower main-stem Colorado River, Arizona-Nevada, but estimated numbers of adults are low and range from less than 100 in Echo Bay up to 200 in Las Vegas Bay (Holden et al. 1999). Most razorback suckers occupying exclusively riverine habitat are now limited to the upper Colorado River basin, and populations are small. The largest riverine population exists in the middle Green River, northeastern Utah and northwestern Colorado (Tyus 1987), and a recent estimate placed the number of adults at about 500 or less (Modde et al. 1996). Modde et al. (1996) characterized the middle Green River population as “precariously” small but dynamic, with at least some recruitment.

Critical habitat designated for razorback sucker makes up about 49% of the species’ original range and occurs in both the upper and lower Colorado River basins (USFWS 1994). River reaches (including the 100-year floodplain) of critical habitat for razorback sucker in the Green River system include the lower 89 km of the Yampa River (i.e., from the mouth of Cross Mountain Canyon to the confluence with the Green River), the Green River between the confluences of the Yampa and Colorado Rivers, the lower 29 km of the White River, and the lower 4 km of the Duchesne River.

4.3.2 Life History Overview

The razorback sucker is adapted to the various habitats and variable hydrologic conditions of the pristine Colorado River system (Minckley 1973, 1983; Holden and Stalnaker 1975a; Behnke and Benson 1983; Carlson and Muth 1989; Lanigan and Tyus 1989; Bestgen 1990; Minckley et al. 1991a). It apparently has a life strategy that includes use of inundated floodplain habitats as growth and conditioning areas (Tyus 1987; Tyus and Karp 1989, 1990, 1991; Modde 1996, 1997; Modde et al. 1995, 1996; Wydoski and Wick 1998). It has a multiphase life cycle, with larvae and early juveniles representing several life-intervals that are morphologically and ecologically distinct from each other and from later juvenile and adult stages (Snyder and Muth 1990). Adults are distinguished by a pronounced bony dorsal keel (“razor”) arising immediately posterior to the occiput. They may attain a maximum length of about 1 m TL (commonly 400–700 mm), weigh 5–6 kg (commonly less than 3 kg), and exceed 40 years of age (Minckley 1983; McCarthy and Minckley 1987). Larvae are generally 7–9 mm TL at hatching, 9–11 mm TL at swim-up. They consume most of their yolk and begin exogenous feeding by 10–11 mm TL (Minckley and Gustafson 1982; Marsh and Langhorst 1988; Papoulias and Minckley 1990; Snyder and Muth 1990). Transition to the juvenile period (*sensu* Snyder 1976) occurs at 27–30 mm TL (Snyder and Muth 1990). Generally, fish greater than 350 mm TL are sexually mature (Minckley 1983; Hamman 1985).

Minckley (1973) stated that razorback suckers in riverine environments make annual spawning “runs” to specific river areas. Razorback suckers in the Green River system spawn over bars of cobble, gravel, and sand substrates during spring-runoff flows at widely ranging flows and water temperatures (McAda and Wydoski 1980; Tyus 1987; Tyus and Karp 1989, 1990; Muth et al. 1998). Reproduction in the lower Colorado River basin generally occurs during January through April (Medel-Ulmer 1983; Minckley 1983; Langhorst and Marsh 1986; Mueller 1989) but may extend from November into May (Bozek et al. 1991; Holden et al. 1999). Estimates of the total fecundity of wild females ranged up to 144,000 ova per fish (Minckley 1983). Presumably, long life and high fecundity allow the species to persist through several consecutive seasons of no or low reproduction and recruitment (Bestgen 1990).

Habitats used by adult razorback suckers in rivers of the upper Colorado River basin include deeper runs, eddies, backwaters, and, at higher flows, flooded off-channel environments in spring (the latter apparently including movements from the colder main channel into warmer habitats, a behavior called "staging," before spawning); runs and pools often in shallow water associated with submerged sandbars in summer; and low-velocity runs, pools, and eddies in winter (Tyus 1987; Osmundson and Kaeding 1989a; Valdez and Masslich 1989; Tyus and Karp 1990; Modde 1997; Modde and Wick 1997; Modde and Irving 1998). Young razorback suckers require nursery environments with quiet, warm, shallow water such as tributary mouths, backwaters, or inundated floodplain habitats in rivers (Smith 1959; Taba et al. 1965; Gutermuth et al. 1994; Modde 1996, 1997; Muth et al. 1998) and coves or shorelines in reservoirs (Minckley et al. 1991a). The diet of all life stages is varied and includes insects, zooplankton, phytoplankton, algae, and detritus (Taba et al. 1965; Vanicek 1967; Hamman 1987; Marsh 1987; Marsh and Langhorst 1988; Muth et al. 1998). Growth to adult size is rapid in warm, food-rich environments (Osmundson and Kaeding 1989b; Minckley et al. 1991a; Mueller 1995).

4.3.3 Research on Razorback Sucker for the 1992 Flaming Gorge Biological Opinion

Two investigations that were conducted in support of the 1992 Biological Opinion on Operation of Flaming Gorge Dam involved research that fully or partially focused on razorback sucker (studies 2 and 3 in Table 1.1). Reports produced from these studies included Lanigan and Tyus (1989), Valdez and Masslich (1989), Tyus and Karp (1990), and Minckley et al. (1991b). Lanigan and Tyus (1989) estimated the number of adult razorback suckers in the middle Green River (RK 282–555) from mark-recapture data and evaluated the status of the population. Valdez and Masslich (1989) characterized the winter habitat and flows for adult Colorado pikeminnow and razorback suckers in a 214-km section of the Green River extending from Ouray, Utah (RK 399), to Browns Park, Colorado (RK 613), with the goal of determining their winter habitat needs. Tyus and Karp (1990) evaluated spawning, movements, and habitat use of adult razorback suckers relative to water flow and temperature regimes during spring in the Green River and lower Yampa River. Minckley et al. (1991b) aged juvenile or adult Colorado pikeminnow and razorback suckers collected from the Green, White, and Yampa Rivers to assess recruitment into existing populations.

4.3.4 Research on Razorback Sucker for the 1990–1996 Flaming Gorge Flow Recommendations Investigation

Studies on razorback sucker conducted during the Flaming Gorge Flow Recommendations Investigation primarily addressed research questions for the spring–summer and winter periods (Table 2.1). Research conducted under this program emphasized development of data to supplement or refine results of earlier studies and focused mostly on reproduction and early life history (Haines 1995; Muth and Meismer 1995; Chart et al. 1999; Modde and Wick 1997; Modde and Irving 1998; Muth et al. 1998) and effects of winter conditions on adults (Valdez 1995; Appendix B of this document). Other selected contemporary studies on or related to the biology of razorback sucker in the Green River that supported the Flaming Gorge Flow Recommendations Investigation concerned invertebrates in main-channel or off-channel habitats (Mabey and Shiozawa 1993; Wolz and Shiozawa 1995), effects of nonnative fishes (Ruppert et al. 1993; Muth and Wick 1997), effects of selenium contamination on reproduction and larval survival (Hamilton and Waddell 1994; Hamilton et al. 1998), population status (Modde et al. 1996), importance and use of inundated floodplain habitats (Modde 1997; Wydoski and Wick 1998), identification and collection of early life stages (Muth and Wick 1997; Snyder 1997; Snyder and Meismer 1997; Proebstel 1998), and effects of physical processes on spawning habitat (Wick 1997; Appendix B of this document).

4.3.5 Ecology of Razorback Sucker in the Green River System

4.3.5.1 Distribution and Abundance

***Before Flaming Gorge Dam*.—**Historic distribution of razorback suckers in the Green River extended from the Colorado River confluence upstream to near Green River, Wyoming (Jordan 1891; Evermann and Rutter 1895; Simon 1946; Sigler and Miller 1963; Baxter and Simon 1970; Vanicek et al. 1970; Quarterone 1993). Smith (1959) stated that razorback suckers were "common in the lower part, but comparatively rare in the upper section of the Green River." The species was apparently rare in the Green River upstream of the Yampa River confluence even before the impoundment of Flaming Gorge Reservoir (Simon 1946; Hubbs and Miller 1953; Smith 1959; Bosley 1960; Gaufin et al. 1960; Smith 1960; Sigler and Miller 1963; Banks 1964; Vanicek et al. 1970; Holden and Stalnaker 1975a). Vanicek et al. (1970) summarized data on the pre-impoundment status of fishes in the Green River from the Flaming Gorge dam site through Dinosaur National Monument and reported the absence of razorback suckers in collections upstream of Willow Creek (RK 616.5; 43.3 km downstream of the dam site). Banks (1964) collected 10 razorback suckers in Dinosaur National Monument during studies on the effects of the 1962 Green River fish poisoning (Holden 1991); accounts of greater numbers of specimens (up to 60) were also related (in Minckley et al. 1991a), but Binns (1965, 1967) suggested that the razorback sucker was the rarest fish observed during and immediately after the poisoning.

***After Flaming Gorge Dam*.—**Although still widely distributed in the main-stem and lower sections of major tributaries, razorback suckers presently occupy only a portion of their former range in the Green River in Utah and Colorado. Fish surveys conducted before and soon after impoundment of Flaming Gorge Reservoir documented the disappearance of razorback suckers from the Green River upstream of the Yampa River confluence after closure of Flaming Gorge Dam (Vanicek et al. 1970). However, Holden and Crist (1981) captured two adult razorback suckers in lower Lodore Canyon during 1978–1980, the years immediately following modification of releases from Flaming Gorge Dam designed to increase summer tailwater temperatures for trout. Also, Bestgen and Crist (2000) captured one adult razorback sucker in lower Lodore Canyon during 1994–1996. Most razorback suckers have been collected from the main stem between RK 282 and 552 (upper portion of Reach 3 through Reach 2; Figure 2.1) and from the lower 21 km of the Yampa River (Vanicek et al. 1970; Holden and Stalnaker 1975b; McAda and Wydoski 1980; Miller et al. 1982a; Tyus et al. 1982a, 1987; Tyus 1987; Lanigan and Tyus 1989; Bestgen 1990; Tyus and Karp

1990; McAda et al. 1994a, 1994b, 1995, 1996, 1997; Muth 1995; Chart et al. 1999; Modde and Wick 1997; Modde and Irving 1998; Muth et al. 1998).

The largest concentration of razorback suckers exists in low-gradient flat-water reaches of the middle Green River (Reach 2) between and including the lower few kilometers of the Duchesne River (confluence, RK 399.3) and Yampa River (confluence, RK 555.1; Tyus 1987; Tyus and Karp 1990; Muth 1995; Modde and Wick 1997; Muth et al. 1998). This area includes the greatest expanse of floodplain habitat in the upper Colorado River basin, between Pariette Draw at RK 383 and the Escalante Ranch at RK 499 (Irving and Burdick 1995). Lanigan and Tyus (1989) used a demographically closed model with capture-recapture data collected from 1980 to 1988 and estimated that the middle Green River population consisted of about 1,000 adults (mean of 948; 95% confidence interval, 758–1,138). On the basis of a demographically open model and capture-recapture data collected from 1980 to 1992, Modde et al. (1996) estimated the number of adults in the middle Green River population at about 500 fish (mean of 524; 95% confidence interval, 351–696). That population had a relatively constant length frequency among years (most frequent modes were in the 505–515 mm-TL interval) and an estimated annual survival rate of 71%. From 1990 through 1996, captures of 149 adult razorback suckers (including recaptures)from the middle Green River were recorded in the Colorado River Recovery Program Centralized Database; 16 of those were from the Basin-Wide Monitoring Program for razorback suckers started in 1996 (McAda et al. 1994a, 1994b, 1995, 1996, 1997; Muth 1995; Muth et al. 1997).

Razorback suckers are presently rare in the lower Green River. Lanigan and Tyus (1989) captured 13 adults from the lower Green River (Reach 3; Figure 2.1) during 1980–1988 but were unable to calculate an abundance estimate. From 1990 through 1996, four adult razorback suckers were collected from the lower Green River during ISMP sampling for subadult and adult Colorado pikeminnow (McAda et al. 1994a, 1994b, 1995, 1996, 1997; Muth 1995).

Adult razorback suckers remaining in the Green River system are few in number (Lanigan and Tyus 1989; Modde et al. 1996) and mainly represented by old fish (Tyus 1987; Minckley et al. 1991b). However, reproduction by razorback suckers in the middle Green River within recent years was documented through collections of larvae (Tyus 1987; Muth et al. 1998), and reproduction in the lower Green River downstream of Green River, Utah (RK 192.9) is suspected on the basis of recent captures of razorback sucker larvae and early juveniles (Muth and Wick 1997; Muth et al. 1998). Reproduction in the lower Green River has not been confirmed by the collection of ripe males and females (Chart et al. 1999). Despite production of larvae, only six early juvenile razorback suckers have been collected from riverine habitats in the Green River since 1990 (Gutermuth et al. 1994; Utah Division of Wildlife Resources, unpublished data). However, Modde (1996, 1997) discovered 73 juveniles in the managed wetland called Old Charlie Wash (a 147-ha depression wetland described by Modde [1997] and Modde and Wick [1997]) adjacent to the middle Green River on the Ouray NWR (Reach 2).

4.3.5.2 Life History by Season

4.3.5.2.1 Spring

4.3.5.2.1.1 Reproduction

Adult movements and habitat use.—Spring migrations by adult razorback suckers were associated with spawning in historic accounts (Jordan 1891; Hubbs and Miller 1953; Sigler and Miller 1963; Vanicek 1967), and a variety of local and long-distance movements and habitat-use patterns have been subsequently documented. McAda and Wydoski (1980) released five male razorback suckers equipped with ultrasonic transmitters into the lower 1 km of the Yampa River and tracked their movements during May 1975. These fish remained within 0.5 km of their release point and were usually found in quiet water near shore. Periodic forays into relatively swift (up to 0.8 m/s), shallow (0.3 m deep) water on the outer edge of a gravel bar at the mouth of the Yampa River were observed for one fish. Tyus (1987) documented both sedentary (movements 0–10 km) and mobile (movements 13–206 km) behaviors for razorback sucker adults in the middle Green River during spring and summer. Spawning migrations (one-way movements of 30.4–106.0 km) observed by Tyus and Karp (1990) included movements between the Ouray and Jensen areas of the Green River and between the Jensen area and the lower Yampa River. Initial movement of adult razorback suckers to spawning sites was influenced primarily by increases in flow and secondarily by increases in water temperature (Tyus and Karp 1990; Modde and Wick 1997; Modde and Irving 1998). Flow and temperature cues may serve to effectively congregate razorback suckers at spawning sites, thus increasing reproductive efficiency and success. Departures from a natural hydrograph may hinder the ability of razorback suckers to form spawning aggregations (Modde and Irving 1998). Blockage of stream passage interrupts spawning movements of adults, as well as dispersal of young fish, and in-stream barriers have been implicated as factors affecting the distribution of razorback suckers (Lanigan and Tyus 1989; Maddux et al. 1993).

Substantial numbers of razorback sucker adults have been found in flooded off-channel habitats, often in the vicinity of mid-channel spawning bars, shortly before or after spawning. Holden and Stalnaker (1975a) reported that razorback suckers concentrated in flooded mouths of washes along the lower Green River in Canyonlands National Park during high flows in early summer 1971. Tyus (1987) located concentrations of ripe fish associated with warm floodplain habitats and in shallow eddies near the mouths of tributary streams (e.g., Ashley Creek). However, no evidence of spawning was discovered at those sites, and Tyus (1987) suggested that razorback suckers stage for reproduction in habitats different than those used for spawning. Similarly, Holden and Crist (1981) reported the capture of 56 adult razorback suckers in the Ashley Creek-Jensen area of the middle Green River from 1978 to 1980, and Tyus and Karp (1990) reported that about 19% of all ripe or tuberculate razorback suckers collected during 1981–1989 (N = 57) were from flooded lowlands (e.g., Old Charlie Wash and Stewart Lake Drain) and tributary mouths (e.g., Duchesne River and Ashley Creek). Radiotelemetry and capture-recapture data compiled by Modde and Wick (1997) and

Modde and Irving (1998) demonstrated that most razorback sucker adults in the middle Green River moved into flooded environments (e.g., floodplain habitats and tributary mouths) soon after spawning. Tyus and Karp (1990, 1991) and Modde and Wick (1997) suggested that use of warmer, more productive flooded habitats by adult razorback suckers during the breeding season is related to temperature preferences (23–25ºC; Bulkley and Pimental 1983) and abundance of appropriate foods (Jonez and Sumner 1954; Vanicek 1967; Marsh 1987; Mabey and Shiozawa 1993; Wolz and Shiozawa 1995; Modde 1997; Wydoski and Wick 1998). Twelve ripe razorback suckers caught in Old Charlie Wash during late May–early June 1986, a year when a high percentage (59%) of all razorback suckers collected were ripe (Tyus 1987), at Green River flows of about 538–566 m^3/s were in good condition, presumably as a result of the abundant food in the wetland (Tyus and Karp 1991). Eight adult razorback suckers collected from Old Charlie Wash in late summer 1995 entered the wetland when it was connected to the river during peak spring flows (Modde 1996). Reduced spring flooding caused by lower regulated river flows, channelization, and levee construction has restricted access to floodplain habitats used by adult razorback suckers for temperature conditioning, feeding, and resting (Tyus and Karp 1990; Modde 1997; Modde and Wick 1997; Wydoski and Wick 1998).

Spawning areas.—Captures of ripe fish and radiotelemetry of adults in spring and early summer were used to locate razorback sucker spawning areas in the middle Green River (Figure 4.5). McAda and Wydoski (1980) found a presumptive spawning aggregation of 14 ripe fish (2 females and 12 males) over a cobble bar (stones 20–50 cm in diameter) at the mouth of the Yampa River during a 2-week period in early to mid-May 1975. These fish were collected from water about 1 m deep with a velocity of about 1 m/s and temperatures ranging from 7 to 16ºC (mean, 12ºC). Tyus (1987) captured ripe razorback suckers in three areas: (1) Island and Echo parks of the Green River in Dinosaur National Monument, including the lower kilometer of the Yampa River; (2) the Jensen area of the Green River from Ashley Creek (RK 481.4) to Split Mountain Canyon (RK 514); and (3) the Ouray area of the Green River, including the lower few kilometers of the Duchesne River. The Jensen area contributed 73% of the 60 ripe razorback suckers caught over coarse sand substrates or in the vicinity of gravel and cobble bars in those three areas during spring 1981, 1984, and 1986; water temperatures at capture locations ranged from 10.5 to 18ºC (mean, 15ºC). Presumed reproduction by razorback suckers in 1984 was hypothesized based on captures of ripe fish and confirmed by seine collections of larvae (N = 33; 10.6–13.6 mm TL) from quiet shorelines downstream of suspected spawning areas. Tyus and Karp (1990) located concentrations of ripe razorback suckers (N = 191) at two sites during spring 1987–1989: (1) the mouth of the Yampa River just before it enters the Green River (7% of the total number collected) and (2) the Green River upstream of Jensen, Utah, adjacent to the Escalante Ranch between RK 486.4 and 504.0 (93% of the total number collected). Ripe fish captured at those sites were from runs associated with bars of cobble, gravel, and sand substrates in water averaging 0.63 m deep with a mean velocity of 0.74 m/s.

More than 99% (1,729 out of 1,735) of the razorback sucker larvae (8–24 mm TL; mean, 12 mm TL) caught in the middle Green River during spring and early summer 1992–1996 by Muth et al. (1998) were from reaches including and downstream of the presumed spawning site near the Escalante Ranch (Figure 4.5). On the basis of the few larvae (N = 6) recorded from collections in the Echo Park area in 1993, 1994, and 1996, reproduction by razorback suckers at the lower Yampa

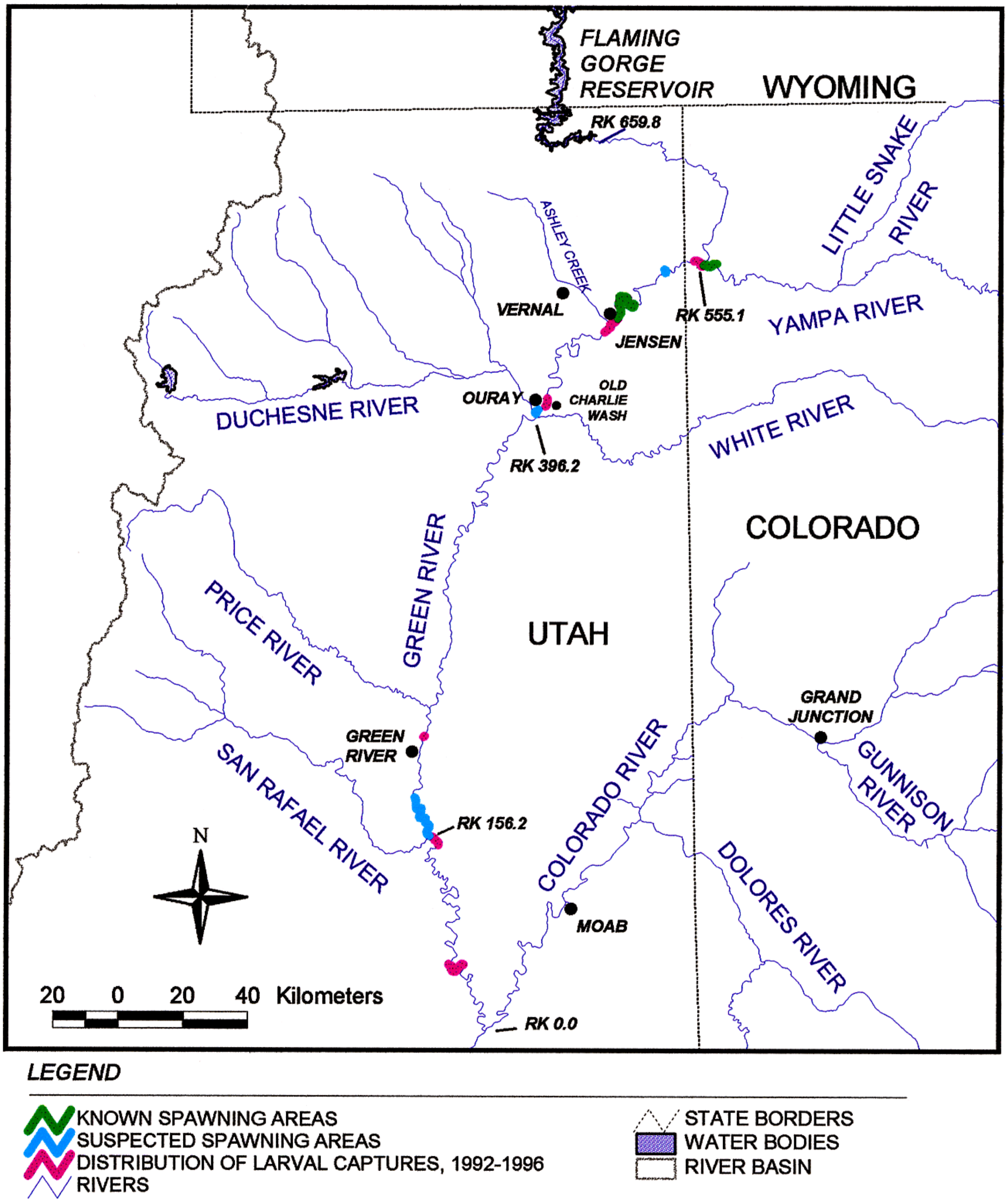
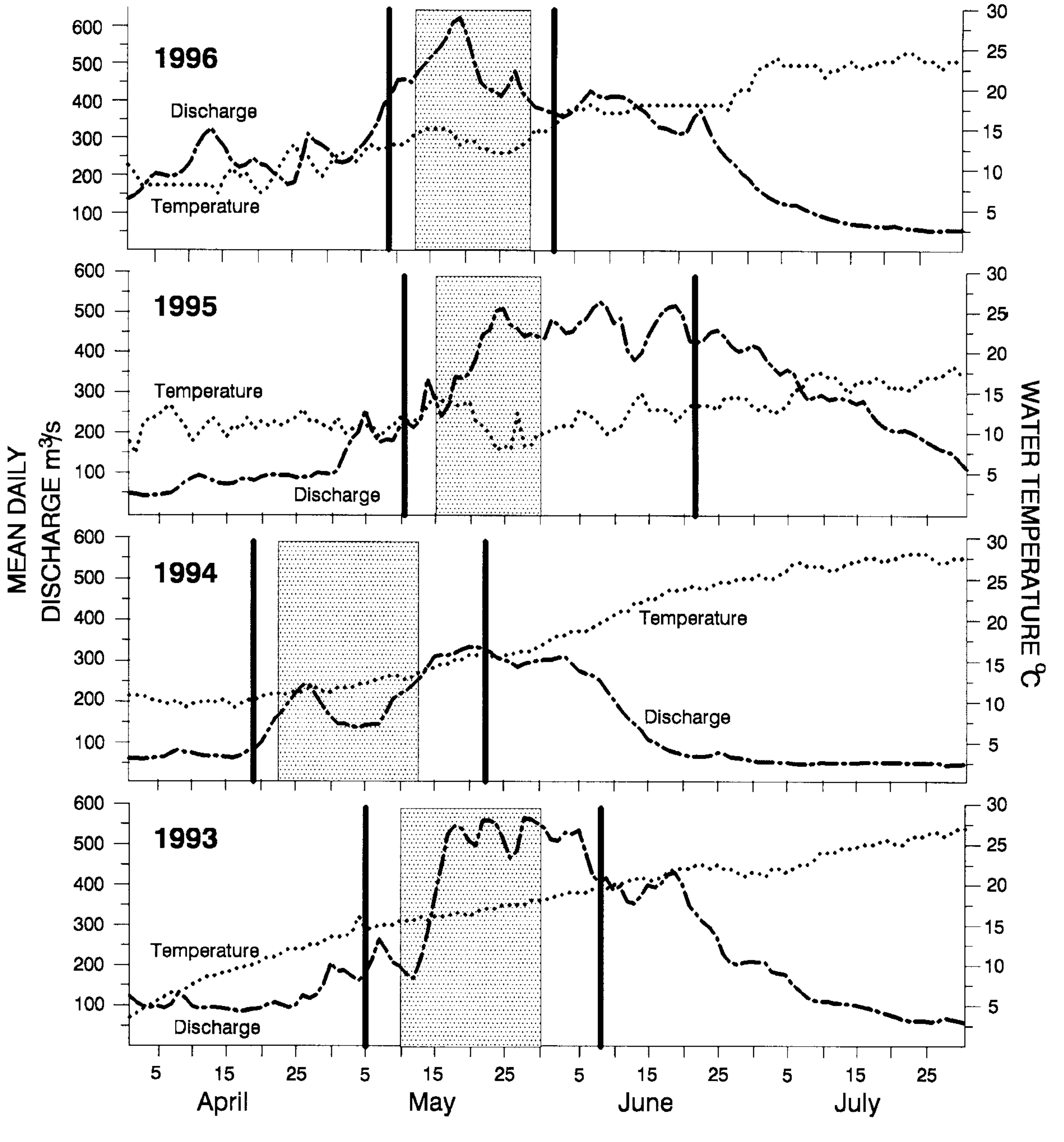


Figure 4.5—Locations of known or suspected razorback sucker spawning areas and the distribution during 1992–1996 of larval razorback sucker captures in the Green River system. Source: Muth et al. (1998)

River spawning site appeared minimal in those years, but sampling efforts in the two river sections immediately downstream of that site were comparatively low (Muth et al. 1998). Although the Escalante site appears to be the primary spawning area for razorback suckers in the middle Green River and fidelity to specific spawning riffles by at least some adults has been suggested (e.g., Tyus and Karp 1990), spawning probably occurs at secondary sites (including the lower Yampa River and possibly the lower portion of Island Park on the Green River), and some ripe fish have been recaptured at different spawning sites within and between years (Tyus 1987; Tyus and Karp 1990; Modde and Wick 1997; Modde and Irving 1998). Natal imprinting on distinctive chemical odors may be involved in selection of spawning sites by adult razorback suckers via olfactory recognition (Wick et al. 1982; Scholz et al. 1992, 1993; Modde et al. 1995).

Tuberculate or ripe razorback suckers have been collected in recent years from reaches of the lower Green River in Labyrinth Canyon near the mouth of the San Rafael River at RK 156.2 (e.g., Tyus 1987; Miller and Hubert 1990; Muth 1995; Chart et al. 1999). Muth et al. (1998) suggested that many of the 439 razorback sucker larvae (10–20 mm TL; mean, 13 mm TL) collected from the lower Green River between RK 45.1 and 156.2 during spring and early summer 1993–1996 had been spawned downstream of RK 176.5 (lower end of the Green River Valley area), possibly near the mouth of the San Rafael River (Figure 4.5). Other evidence for razorback sucker reproduction in the lower Green River includes the collection of two early juveniles at RK 89.5 on 30 July 1991 (Gutermuth et al. 1994) and the capture of 15 larvae (13–16 mm TL), presumably produced in the Green River, from the Colorado River inflow to Lake Powell on 22 June 1993 (Muth and Wick 1997).

Spawning periods and associated river flows and temperatures.—Reproduction by razorback suckers occurs in April through June (commonly May through June) at increasing and highest runoff flows and warming water temperatures, as evidenced by captures of ripe fish (McAda and Wydoski 1980; Tyus 1987; Tyus and Karp 1989, 1990; Modde and Wick 1997) and analysis of larval collections (Muth et al. 1998). Tyus and Karp (1990) caught ripe razorback suckers from mid to late April through May in the middle Green and lower Yampa Rivers, 1987–1989. They associated razorback sucker reproduction in the middle Green River during these low-to-average runoff years (mean flow less than 128 m^3/s; USGS gage near Jensen, Utah) with flows of about 150–250 m^3/s and water temperatures of 9–17°C. Flows and water temperatures associated with spawning in the lower Yampa River ranged from approximately 100 to 160 m^3/s (USGS gage at Deerlodge Park, Colorado) and 10.5 to 16°C, respectively. Spawning by razorback suckers in the Yampa River in 1975, 1981, 1988, and 1989 was believed to occur at flows ranging from about 70 m^3/s in 1989 to 400 m^3/s in 1975 and at water temperatures averaging 15°C (Tyus and Karp 1989). In the middle Green River during 1993–1996, Muth et al. (1998) estimated that razorback sucker spawning extended from mid-April (1994) through late June (1995) but generally ranged from early or mid-May through late May or early June (Figure 4.6). Spawning in 1993, 1995, and 1996 was concentrated during mid to late May, whereas most spawning in the low-flow year of 1994 occurred during April to mid-May. During the reproductive periods from 1993 to 1996, mean daily flows of the main-stem middle Green River ranged from 78 m^3/s in 1994 to 623 m^3/s in 1996 (mean, 370 m^3/s), and instantaneous daily water temperatures ranged from 8.0 to 19.5°C (mean, 14°C; USGS gage at Jensen). In the lower



Heavy vertical lines delimit the range of spawning dates for each year; shaded area indicates estimated periods of peak spawning. Mean daily flows and instantaneous daily water temperatures were recorded by the USGS at the gage near Jensen, Utah.

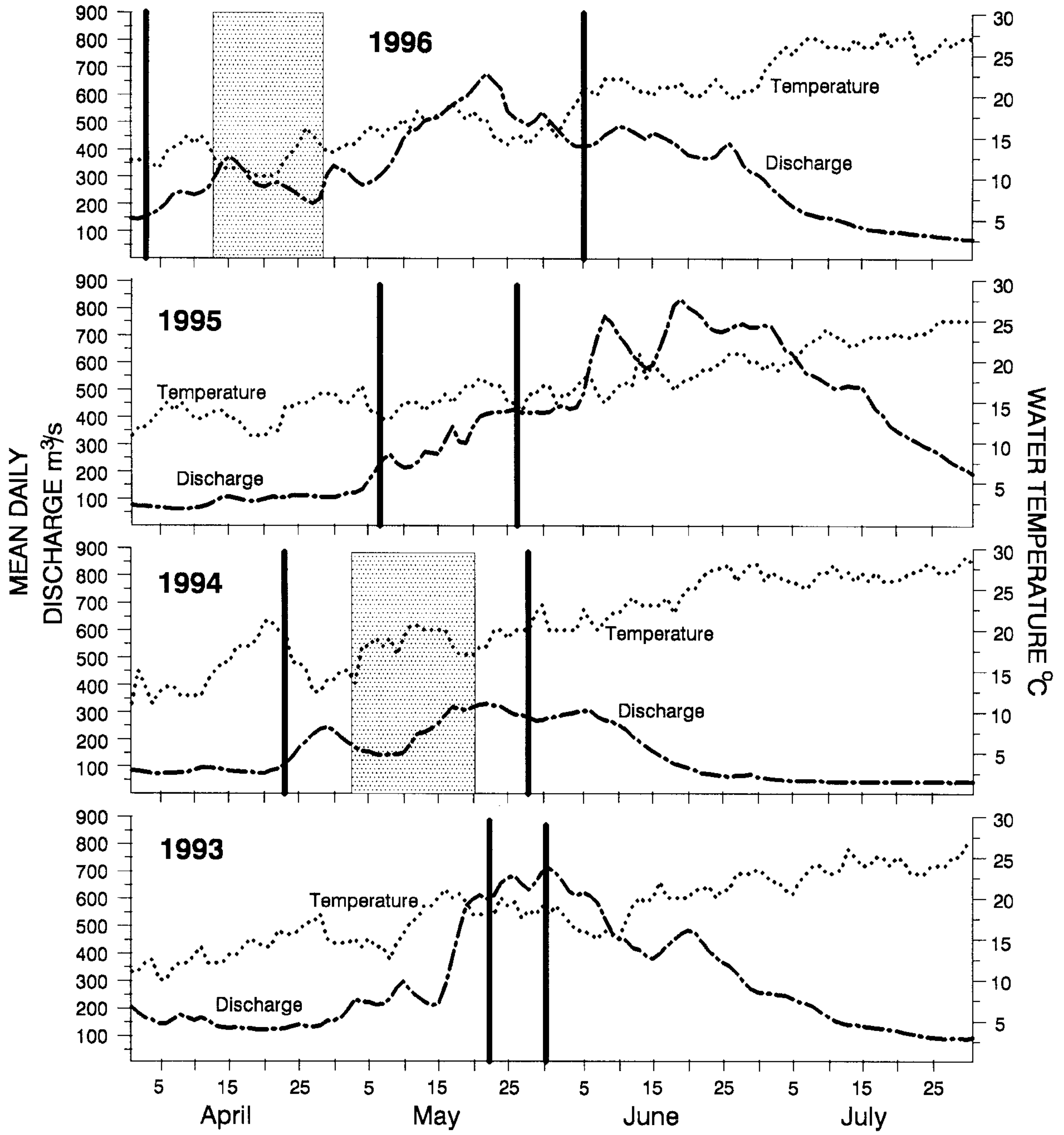
Figure 4.6.—Estimated annual spawning periods of razorback sucker (based on wild-caught otolith-aged larvae) and associated main-stem flows and temperatures in the middle Green River (Reach 2), Utah and Colorado, 1993–1996. Source: Muth et al. (1998)

Green River, Muth et al. (1998) estimated that razorback sucker spawning occurred from late April through late May in 1994 at main-stem flows of 134–331 m^3/s (mean, 233 m^3/s) and water temperatures of 12.5–20.5°C (mean, 17.5°C). Reproduction in 1996 occurred from early April through June in 1996 at flows of 145–679 m^3/s (mean, 376 m^3/s) and water temperatures of 10–21°C (mean, 14.5°C; USGS gage at Green River, Utah; Figure 4.7). Most spawning in the lower Green River occurred during early through mid-May in 1994 and mid through late April in 1996. Muth et al. (1998) observed that estimated dates of first reproduction by razorback suckers in the Green River in most years generally coincided with a relatively steep and consistent increase in flow during the beginning of spring runoff. They concluded that spawning was probably triggered by a suite of interacting environmental cues that could not be detected by their analysis of single water temperature and flow parameters.

Spawning behavior.—On the basis of Balon's classification of reproductive styles of fishes (Balon 1975), the razorback sucker is a nonguarding, open-substrate lithophil (i.e., rock and gravel spawner, eggs deposited in substrate interstices, newly hatched larvae remain hidden in substrate interstices until swim-up). Direct observation of spawning behavior and release of gametes in the Green River was prevented by high water turbidity (Tyus 1987; Tyus and Karp 1990). However, Mueller (1989) observed razorback suckers spawning in the clear Colorado River downstream of Hoover Dam, Arizona-Nevada, and reported behavior similar to that reported for populations in lower basin reservoirs. In Lake Mohave, spawning groups of one female and several male razorback suckers congregate over coarse cobble in water 0.5–5.0 m deep. The males press against the female, and spawning convulsions (a few seconds in duration) sweep the substrate clear of fine materials and create depressions 20 cm or more deep. Individual females have been observed spawning hourly and daily on successive days within a week. The number of eggs released by a female with each spawning act apparently is only a small fraction of her total complement (Minckley et al. 1991a). McAda and Wydoski (1980) estimated the total fecundity of 10 razorback suckers (446–534 mm TL) caught in the Green River during autumn at 27,614–76,576 ova/fish, whereas estimates of total fecundity for five razorback suckers (391–570 mm standard length) collected from Lake Mohave during spring ranged from 74,600 to 144,000 ova/fish (Minckley 1983).

4.3.5.2.1.2 Embryos

The incubation time and hatching success of razorback sucker embryos are temperature dependent. Marsh (1985) evaluated the effects of temperatures ranging from 5 to 30°C on the incubation and hatching success of captive razorback sucker embryos acclimated at 18°C. Total mortality of embryos occurred at 5, 10, and 30°C. When embryos survived, hatch duration was longest (204 h) and percent hatch was highest (35%) at 20°C; hatch duration was shortest (96 h) at 25°C; and percent hatch was lowest (19%) at 15°C. Bozek et al. (1990) reported that hatching success of captive razorback sucker embryos that had become acclimated to experimental temperatures ranged from 22 to 57% at 10°C, 32 to 65% at 15°C, and 34 to 65% at 20°C; total mortality occurred at 8°C. They concluded that suitable hatching temperatures were 12–20°C. Hatching time for 50% of the eggs was 420–556 h at 10°C, 256–298 h at 15°C, and 158–168 h at 20°C. Haines (1995)



Heavy vertical lines delimit the range of spawning dates for each year; shaded area indicates estimated periods of peak spawning. Estimates of spawning periods in 1993 and 1995 are questionable because of abbreviated larval sampling (1993) or low capture of larvae (1995; $N = 5$). Mean daily flows and instantaneous daily water temperatures were recorded by the USGS at the gage near Green River, Utah.

Figure 4.7.—Estimated annual spawning periods of razorback sucker (based on wild-caught otolith-aged larvae) and associated main-stem flows and temperatures in the lower Green River (Reach 3), Utah, 1993–1996. Source: Muth et al. (1998)

evaluated the effects of temperature (12, 16, and 20ºC) on the developmental rate and hatching success of captive embryos of razorback and flannelmouth suckers. The mean number of days between fertilization and peak hatch decreased as temperature increased for both species and ranged from 6.5 to 12.5 d for razorback sucker and 6.0 to 16.5 d for flannelmouth sucker. The period from first to last hatch averaged 2.0 d longer for razorback sucker than for flannelmouth sucker over all temperatures. The percent hatch for flannelmouth embryos was independent of temperature and, at each temperature, was greater (83–91%) than the percent hatch for razorback sucker embryos (48–67%); hatching success of razorback sucker embryos increased as temperature increased.

Several factors may limit the survival of razorback sucker embryos in the Green River system. These factors include reduced water temperatures in upstream areas caused by operation of Flaming Gorge Dam (Tyus and Karp 1991), sedimentation of cobble and gravel spawning substrates associated with high releases from Flaming Gorge Dam occurring too early in the spring runoff period (Wick 1997), predation on eggs by nonnative fishes (Hawkins and Nesler 1991; Lentsch et al. 1996b; Tyus and Saunders 1996), and selenium contamination of adults and embryos (Hamilton and Waddell 1994).

4.3.5.2.1.3 Larvae

Before 1992 (Muth et al. 1998), direct evidence of reproduction by razorback suckers in the upper Colorado River basin or information on the species' early life history in riverine environments were limited to collections of larvae by Tyus (1987) and captures of a few early juveniles from backwaters (e.g., Smith 1959; Taba et al. 1965; Gutermuth et al. 1994). Diagnostic characters for distinguishing larval razorback suckers from larvae of sympatric suckers (e.g., bluehead and flannelmouth suckers) were only recently developed (Snyder and Muth 1990), and previous sampling for riverine razorback suckers did not target early life stages. Razorback sucker larvae are generally 7–9 mm TL at hatching and 9–11 mm TL at swim-up; at 15ºC, larvae swim up 13 d after hatching (Minckley and Gustafson 1982; Marsh 1985; Snyder and Muth 1990; R. T. Muth, personal observation). In rivers, larval razorback suckers presumably enter the drift after emerging from spawning substrates (Mueller 1989; Paulin et al. 1989) and are transported downstream into off-channel nursery environments with quiet, warm, shallow water (e.g., tributary mouths, backwaters, and inundated floodplain habitats).

Captures in spring and early summer 1992–1996 (Muth et al. 1998).—Sampling for razorback sucker larvae was conducted in five sections of the middle Green River in Reach 2 — Echo Park (RK 553.5–555.1), Island-Rainbow Park (RK 526.1–534.2), Escalante (RK 487.5–500.7), Jensen (RK 466.1–485.6), and Ouray (RK 399.8–420.2) — and in three sections of the lower Green River in Reach 3 — Green River Valley (RK 176.5–210.4), San Rafael River confluence (RK 151.3–159.4), and lower Labyrinth-upper Stillwater Canyon (RK 40.7–55.1). These areas were selected because of their close proximity to known razorback sucker spawning sites or reported captures of individual tuberculate or ripe fish and because they had quiet-water habitats available to fish larvae under varied river flows. Habitats for fish larvae included ephemeral shoreline embayments (e.g., backwaters) — particularly ponded lower portions of flooded tributary streams — and side canyons, washes, canals, or channels. These low-velocity habitats were generally less than 1 m deep and moderately turbid, and they had predominantly silt and sand or silt and mud substrates, sparse to dense emergent macrophytes near shorelines, and low-velocity eddies at their interface with the main channel. They generally persisted through at least mid-summer each year, and they are primary nursery areas for fish larvae in spring and early summer under the present regulated flow regime of the Green River.

Razorback sucker larvae were collected each year during 1992–1996, but mean catch rates (catch per unit effort; CPUE) were highly variable among years and river sections. Muth et al. (1998) stated that temporal and spatial variations in catch data were expected because of inherent variability in biological and physical processes, but they were uncertain if their CPUE estimates were true indicators of population abundance or biased by differences in sampling efficiency. Numbers of razorback sucker larvae captured per year ranged from 20 in 1992 to 1,217 in 1994 for the middle Green River and from 5 in 1995 to 222 in 1996 for the lower Green River. In the middle Green River (Figure 4.5), the Escalante (711 larvae), Jensen (700), and Ouray (318) areas combined produced more than 99% of the total catch. More than 70% of all razorback sucker larvae collected from the Escalante area were caught in Cliff Creek (an intermittent tributary stream joining the Green River at RK 487.5); 83, 11, and 6% of those captured from the Jensen area were in collections from Stewart Lake Drain (an outlet canal from Stewart Lake at RK 481.7), backwaters in the Red Wash Launch area (approximately RK 480–481), or Sportsmans Drain (an outlet canal from Uintah Sportsmans Club Lake at RK 477.4), respectively. Most larval razorback suckers (85%) caught in the Ouray area were from Greasewood Corral (a side channel at RK 405.6) or the inlet to Old Charlie Wash at RK 405.4 (14%).

Collections in the lower Green River during 1993–1996 produced the first-ever captures of razorback sucker larvae from this section of river (Figure 4.5). A total of 363 larval razorback suckers were caught in the lower Labyrinth-upper Stillwater Canyon area (80% from Millard Canyon, a flooded side canyon at RK 53.9; and 19% from flooded washes, backwaters, and side channels in the Anderson Bottom-Bonita Bend area, RK 49.9–50.7); 76 were caught in the San Rafael River confluence area (all from flooded habitats at or immediately downstream of the mouth of the San Rafael River); and one was caught in a backwater of the Green River Valley area.

***Diet*.**—Larval razorback suckers consume most of their yolk and begin exogenous feeding on planktonic or benthic organisms by the time they reach 10–11 mm TL (Minckley and Gustafson 1982; Marsh and Langhorst 1988; Papoulias and Minckley 1990; Snyder and Muth 1990; USFWS 1998a). Muth et al. (1998) analyzed the diet of razorback sucker larvae 11–18 mm TL collected from nursery habitats in the middle or lower Green River during 1993–1996. In both river sections, the percentage of razorback suckers with food in their digestive tracts and the mean percent fullness of digestive tracts increased as fish length increased. Digestive tracts of all fish larger than 13 mm TL contained food and averaged more than 50% full. Principal dietary components were early instar chironomid larvae, small cladocerans, rotifers, algae, and organic and inorganic debris, but the relative importance of these food categories varied with fish length. Although chironomids were the dominant food item in guts of fish of all lengths, their proportional contribution to the diet generally increased or remained high with increasing fish length. Conversely, the relative importance of cladocerans, rotifers, and algae tended to decrease as fish length increased. Most digestive tracts contained debris, which accounted for moderate proportions of gut contents (10–30% of food volume) for all TL intervals. Debris consisted of fine, amorphous particles of organic matter, clay particles, and sand grains. Larval razorback suckers from the lower Green River consumed slightly more algae than those from the middle Green River. Ephemeroptera larvae were eaten by fish larger than 14 mm TL, whereas copepods, ostracods, and invertebrate eggs were found in guts of fish smaller than 15 mm TL.

Similar to observations by Muth et al. (1998), findings on hatchery-produced razorback sucker larvae recaptured 1 week after stocking in a backwater of the Salt River, Arizona, indicated that they had consumed primarily larval chironomids (reviewed by Bestgen 1990). This dietary pattern indicates opportunistic feeding because chironomids are among the more common benthic invertebrates in quiet-water, soft-sediment riverine habitats of the Colorado River basin (Ward et al. 1986; Grabowski and Hiebert 1989; Muth and Snyder 1995; Wolz and Shiozawa 1995). In contrast, Marsh and Langhorst (1988) reported that larval razorback suckers less than 21 mm TL from a shoreline section of Lake Mohave and an adjacent, isolated backwater without nonnative fishes ate primarily rotifers, cladocerans, or copepods. However, the diet of larvae in the backwater was comparatively more diverse and included larval chironomids and trichopterans. The digestive tracts of 33% of all specimens (41 of 124) from Lake Mohave and 63% of all specimens (47 of 75) from the backwater contained food. Similar to the isolated backwater, Muth et al. (1998) found food in the digestive tracts of 67% of 480 larval razorback suckers; food was in 59% of 379 specimens 11–13 mm TL (which averaged 35–45% full) and 100% of all specimens 14–18 mm TL (which averaged 51–65% full).

Growth and survival.—The food-limited growth and survival of razorback sucker larvae have been postulated as contributing to the low or nonexistent recruitment (Minckley 1983; Marsh and Langhorst 1988; Papoulias and Minckley 1990, 1992; Modde 1997). Muth et al. (1998) reported that mean and maximum TL of larval razorback suckers in collections from the middle or lower Green River generally increased as sampling progressed each year, and approximately 20% of all larvae captured were larger than 12 mm TL; the two largest specimens were 20 and 24 mm TL. They estimated that mean daily growth (posthatching) of larvae less than 35 d old collected from either river section during 1993–1996 was lowest in 1994 (0.31 and 0.27 mm TL/d for the middle and lower Green River, respectively) and greatest in 1996 (0.35 and 0.33 mm TL/d). Over all years, specimens from the middle Green River grew 6–21% faster than those from the lower Green River. Muth et al. (1998) noted that, although food abundance in existing Green River nursery habitats appeared adequate to meet at least the minimum nutritional requirements for larval survival, growth of razorback sucker larvae was not optimal. For example, mean laboratory growth rates of larval razorback suckers fed nauplii of *Artemia* sp. *ad libitum* twice daily for 28 d after the start of exogenous feeding were 0.39, 0.57, 0.65, or 0.72 mm TL/d at constant water temperatures of 16.5, 19.5, 22.5, or 25.5°C, respectively (K. R. Bestgen, personal observation).

Relatively minor differences in growth rates can be biologically significant if size-dependent processes, such as predation by small, gape-limited predators, are important regulators of larval survival (Section 4.2). For example, Bestgen et al. (1997) demonstrated through experiments and recruitment-model simulations that the predatory effects of nonnative adult red shiners on the mortality of larval Colorado pikeminnow decreased 5–40% as growth rates of larvae increased by 0.1-mm increments from 0.2 to 0.6 mm TL/d. Predation by adult red shiners on larvae of native catostomids in flooded and backwater habitats of the Yampa, Green, or Colorado Rivers was documented by Ruppert et al. (1993) and Muth and Wick (1997). Horn (1996) concluded that although nutritional limitations in Lake Mohave may directly contribute to the high mortality of larval razorback suckers, a greater problem is reduced growth, which keeps larvae at a size vulnerable to predation for a longer period of time. He further stated that apparently all razorback sucker larvae in Lake Mohave, starving or not, are consumed by nonnative fish predators.

Predation by nonnative fishes on young razorback suckers is considered a serious threat to populations (Bestgen 1990; Minckley et al. 1991a; Horn 1996; USFWS 1998a; Johnson and Hines 1999). Ruppert et al. (1993) and Wydoski and Wick (1998) reported that because razorback suckers in the Green River system spawn on the ascending limb of the hydrograph and their larvae disperse into low-velocity habitats during May and June when invertebrate numbers are typically low in riverine nursery habitats, razorback sucker larvae would be highly susceptible to predation by nonnative fishes at that time because other food organisms are scarce. Muth et al. (1998) suggested that the extremely low survival of larval razorback suckers in the Green River during 1992–1996 was based on the apparent disappearance of larvae from nursery habitats by early or mid-July each year. Thus it appears that low survival of early life stages is responsible for the extremely low recruitment in wild populations.

Historically, floodplain habitats inundated and connected to the main channel by overbank flooding during spring runoff would have been available as nursery areas for young razorback suckers in the Green River. Tyus and Karp (1990) associated low recruitment with reductions in floodplain inundation since 1962 (closure of Flaming Gorge Dam), and Modde et al. (1996) associated years of high spring flow and floodplain inundation in the middle Green River (1983, 1984, and 1986) with subsequent suspected recruitment of young adult razorback suckers. Floodplain habitats are typically warmer and substantially more productive than the adjacent river and have abundant vegetative cover (Mabey and Shiozawa 1993; Wolz and Shiozawa 1995; Modde 1997; Wydoski and Wick 1998; Crowl et al. 1998a). Spawning at increasing and highest runoff flows gives drifting razorback sucker larvae maximum access to flooded habitats, and enhanced growth of larvae in those habitats may increase their overall survival by shortening the period they are vulnerable to predation (Lentsch et al. 1996a).

Early juvenile razorback suckers were recently found during the late summer and autumn draining of Old Charlie Wash (Modde 1996, 1997). Despite the predominance of nonnative fishes (including several known fish predators), 28 razorback sucker juveniles (74–125 mm TL; mean, 94 mm) were collected from the wetland in October 1995, and 45 (44–83 mm TL; mean, 66 mm) were collected in August 1996 (Table 4.5). It is unknown whether these fish originated from riverine

Table 4.5.—Examples of mean daily growth (total length [TL] increment) of age-0 razorback suckers in fertilized hatchery ponds, in off-channel nursery habitats on the middle (Utah and Colorado) or lower (Utah) Green River, or in the managed wetland, Old Charlie Wash, adjacent to the middle Green River.

Hatchery Ponds[a] (cumulative growth of captive larvae over weekly periods after start of rearing at about 10 mm TL)		**Off-Channel Habitats**[b] (growth of wild larvae between hatching and capture)		**Old Charlie Wash**[c] (growth of wild larvae and early juveniles over periods after larvae entered the wetland)	
Week	Daily growth (mm TL/d)	Green River section and year	Daily growth (mm TL/d)	Year and estimated days between larvae entering the wetland and capture of early juveniles	Daily growth (mm TL/d)
1	0.03	Middle; 1993	0.34	1995; 81 d	0.79–1.42
2	0.09	1994	0.31	98	0.65–1.17
3	0.16	1995	0.34	105	0.61–1.10
4	0.17	1996	0.35	122	0.52–0.94
5	0.17	Lower; 1993	0.30	1996; 36 d	0.94–2.03
6	0.21	1994	0.27	53	0.64–1.38
7	0.26	1995	0.28	59	0.58–1.24
8	0.27	1996	0.33	76	0.45–0.96

[a] Estimated from weekly mean TL reported by Papoulias and Minckley (1992) for larvae stocked at 250,000 per ha in earthen ponds treated with 341 kg of commercial alfalfa pellets and 57 kg of PO_4 per ha ("high" fertilization treatment).

[b] Estimated from otolith-aged larvae collected from off-channel flooded (e.g., tributary mouth, side canals, side canyons, and washes) or backwater habitats (Muth et al. 1998). Larvae at capture were 10.4–20.3 mm TL (mean, 12.3 mm) and 6–34 d old (mean, 14 d).

[c] Estimated from captures of larvae (Muth et al. 1998) and collections of early juveniles during draining of Old Charlie Wash in October 1995 and August 1996 (Modde 1996, 1997). Early juveniles at capture were 74–125 mm TL in 1995 and 44–83 mm TL in 1996. It was assumed that early juveniles grew from larvae (mean, 10 mm) that entered the wetland when it was connected to the main channel.

spawning and drifted into Old Charlie Wash as larvae or were spawned in the wetland. Wydoski and Wick (1998), on the basis of captures of ripe fish, suggested that razorback suckers may spawn in floodplain habitats under certain conditions, but no evidence exists to support this supposition. During 1995 and 1996, small riverine fishes had access into Old Charlie Wash through the inlet canal when Green River flows exceeded about 240 m^3/s. Over-dike flooding of the wetland occurred from 21 May to 2 July in 1995 and from 8 May to 14 June in 1996 when Green River flows exceeded about 396 m^3/s. Eight adult razorback suckers (461–525 mm TL; 1034–1650 g) were found in Old Charlie Wash. Six were found before draining and two were found during draining in 1995 (Modde 1996, 1997). Modde (1997) reported that favorable nursery conditions existed in Old Charlie Wash during spring and summer each year. For example, the habitat had abundant zooplankton (peak mean density of organisms collected with a 243-Fm mesh plankton net towed near the surface was 54.3/L in 1995 and 42.8/L in 1996), warm water (about 16–28ºC, 2–8ºC higher than the adjacent river), abundant vegetative cover, surface dissolved oxygen ranging from 4 to 11 mg/L, and water depths ranging from about 1 to 2.5 m. Mabey and Shiozawa (1993) collected benthos (1.27-cm diameter core sample) and zooplankton (63-Fm mesh plankton net towed vertically) from floodplain (Old Charlie Wash), backwater, and main-channel habitats of the middle Green River near Ouray in summer 1991. For the first sampling period in each habitat, they reported that the density of benthos was 41 times greater in Old Charlie Wash (85,812–262,808/m^2 over all sampling periods) than in the other habitats (4,806–23,059/m^2 in backwaters and 948–6,138/m^2 in the main channel), and that the density of zooplankton was 29 times greater in Old Charlie Wash (205.9–690.2/L) than in backwaters (1.5–63.4/L) and 157 times greater in Old Charlie Wash than in the main channel (0.3–1.3/L). A comparison of estimated mean daily growth (TL increment) of age-0 razorback suckers in fertilized hatchery ponds, in off-channel nursery habitats along the middle (Reach 2) or lower Green River (Reach 3) during 1993–1996, and in Old Charlie Wash (1995 and 1996) demonstrated that even the slowest growth rate in Old Charlie Wash (0.45 mm/d) was 67% greater than the fastest growth rate in the hatchery ponds (0.27 mm/d) and 29% greater than the fastest growth rate in the off-channel nursery habitats (0.35 mm/d; Table 4.5).

4.3.5.2.2 Summer and Autumn

4.3.5.2.2.1 Juveniles

Little is known about the biology of juvenile razorback suckers, but the few collected from rivers were found in quiet-water habitats. In 1950, about 6,600 larval or early juvenile razorback suckers were seined along warm, shallow margins of the Colorado River at Cottonwood Landing, Nevada (Sigler and Miller 1963). Smith (1959) caught two juveniles (both about 38 mm long) in the Glen Canyon area of the Colorado River before it was inundated by Lake Powell, one fish from a backwater and one from a flooded tributary mouth. Taba et al. (1965) collected eight razorback sucker juveniles (90–115 mm long) from backwaters on the Colorado River near Moab, Utah, in 1962–1964. The digestive tracts of those fish contained “algae and bottom ooze.” Juvenile razorback suckers have been caught in lateral canals off the lower Colorado River (Marsh and Minckley 1989; Maddux et al. 1993). Stocked, hatchery-produced young have been observed along shorelines, in embayments, along sandbars, or in tributary mouths, eventually moving into river channels or larger backwaters (Minckley et al. 1991a).

Despite production of larvae, only six early juvenile razorback suckers have been collected from backwaters in the Green River since 1990. Gutermuth et al. (1994) caught two specimens (36.6 and 39.3 mm TL; estimated posthatching ages were 54 and 58 d) in a backwater on the lower Green River (Reach 3) near Hell Roaring Canyon (RK 89.5) on 30 July 1991. This record was the first verified evidence of razorback sucker survival beyond the larval period in the upper Colorado River basin since that reported by Taba et al. (1965). The remaining four fish were collected by the Utah Division of Wildlife Resources (unpublished data); two (37 and 39 mm TL) were captured in 1993 from a backwater on the Ouray NWR (Reach 2), and two (both 29 mm TL) were captured in 1994 from backwaters in Desolation Canyon (RK 260.2 and 291.4) (Reach 3). The discovery of 73 wild razorback sucker early juveniles in Old Charlie Wash on the middle Green River (Modde 1996, 1997) represents the largest number ever reported in the upper Colorado River basin and demonstrated that floodplain habitats are important nursery areas.

4.3.5.2.2.2 Adults

Outside the breeding season, adult razorback suckers tend to utilize deeper eddies, backwaters, and pool-type habitats (Minckley et al. 1991a), and their movements are generally reduced (Tyus 1987; Tyus and Karp 1990). Habitat use in rivers of the upper Colorado River basin in summer and autumn included submerged mid-channel sandbars, pools, eddies, and runs (Tyus 1987; Osmundson and Kaeding 1989a; Modde and Wick 1997). Tyus (1987) reported that during summer, Green River fish occupied uneven mid-channel sandbars in water less than 2 m deep with a mean velocity of 0.5 m/s. Habitat use in the middle Green River during spring and summer 1993 included runs, eddies, and run-eddy interfaces in water 1–3 m deep over sand, cobble, and gravel substrates (Modde and Wick 1997; Modde and Irving 1998). Although turbulent canyon reaches are not considered preferred habitat for razorback suckers (Tyus 1987; Lanigan and Tyus 1989; Minckley et al. 1991a), Modde and Wick (1997) and Modde and Irving (1998) reported that six radio-tagged adults moved into or near the vicinity of Split Mountain Canyon (Reach 2) during summer or autumn in 1993 and 1994 and possibly remained there over winter. Ryden and Pfeifer (1998) reported that large juvenile and adult razorback suckers stocked in the San Juan River in New Mexico and Utah preferred fast, mid-channel habitats during the summer–autumn base-flow period.

4.3.5.2.3 Winter

Radiotelemetry was used to determine winter movements and habitat use of adult razorback suckers in rivers. McAda and Wydoski (1980) and Valdez and Masslich (1989) reported that fish in the middle Green River overwintered in the Jensen, Island Park, and Echo Park areas. Overwintering in or near Split Mountain Canyon was also suspected (Modde and Wick 1997; Modde and Irving 1998). Valdez and Masslich (1989) found that razorback suckers preferred overwintering sites in moderately deep, low-velocity habitats and moved only locally, between microhabitats, except during flow changes (e.g., increased flows or flow fluctuations) or to avoid ice jams and frazil-ice masses. Most overwintering adults in the Green River moved distances of less than about 5 km at rates of 25–31 m/h and used slow runs, slack waters, and eddies where water depth averaged 0.6–1.4 m and water velocity averaged 0.03–0.3 m/s. Valdez and Masslich (1989) concluded that flow fluctuations greater than 5 cm/h caused about 39% more movement in adult razorback suckers; additional movement was observed when maximum flow fluctuations in January and February caused buildup and transport of ice. Osmundson and Kaeding (1989a) reported that during November through April, adult razorback suckers in the Colorado River, Colorado, were primarily found in pools and slow eddies at depths of about 2 m. High habitat complexity was characteristic of reaches occupied during winter by large juvenile and adult razorback suckers stocked in the San Juan River, and low-velocity habitat at edges of pools was determined to be "vitally" important (Ryden and Pfeifer 1998).

4.3.6 Summary of Seasonal Flow-Habitat Relationships for Razorback Suckers in the Green River System

This section focuses on the seasonality of razorback sucker life history in the context of flow-habitat relationships in the Green River system. Table 4.6 at the end of this section summarizes flow and temperature needs by season and river reach. Information summarized here from preceding sections was used to make integrated flow and temperature recommendations to benefit endangered fishes in the Green River downstream of Flaming Gorge Dam (Chapter 5).

4.3.6.1 Spring

Razorback suckers spawn in areas of the middle Green and lower Yampa Rivers (Reach 2), and they are suspected to reproduce in the lower Green River downstream of Green River, Utah (Reach 3; Figure 4.5). The initial movement of adults to spawning areas in spring appears to be influenced primarily by increases in flow, and reproduction occurs at increasing and highest runoff flows and warming water temperatures (Figures 4.6 and 4.7). Estimated annual spawning periods encompassed a wide range of river temperatures (8–21ºC) and flows (134–679 m^3/s in the lower Green River, 78–623 m^3/s in the middle Green River, and 70–400 m^3/s in the lower Yampa River). Bozek et al. (1990) concluded that suitable hatching temperatures for razorback sucker embryos were 12–20ºC. The predominance of razorback sucker larvae 11–12 mm TL in collections during spring and early summer 1992–1996 from the middle and lower Green River suggested continuous spawning and larval production (Muth et al. 1998). The wide ranges in flow and temperature during spawning suggest that the razorback sucker is adapted for reproduction in a highly variable environment. However, observations from the Green River suggest that the level of spawning activity (Tyus 1987) or larval production (Muth et al. 1998) varies among years.

Most collections of wild adult razorback suckers in rivers of the upper Colorado River basin have occurred in unconfined floodplain reaches (Modde et al. 1995; Muth 1995), and most known historic spawning aggregations were located upstream of areas with broad floodplains (Wydoski and Wick 1998). The greatest expanse of floodplain habitat in the upper basin is in the Ouray and Jensen areas of the middle Green River, coincident with the largest extant reproducing riverine population of razorback suckers. Floodplain habitats inundated and connected to the main channel by spring runoff appear to be important habitats for all life stages of razorback sucker, and the seasonal timing of razorback sucker reproduction suggests they have adapted to utilizing these habitats. However, most floodplain areas adjacent to the Green River are now isolated from the main channel by levees, and the historic frequency, magnitude, and duration of seasonal overbank flooding in the Green River have been substantially reduced since closure of Flaming Gorge Dam.

The natural integrity of large-river ecosystems is dependent on interactions between the main channel and floodplain (Welcomme 1985, 1995; Junk et al. 1989; Ward 1989; Petts and Maddock 1994; Stanford 1994; Ward and Stanford 1995; Brookes 1996; Wetzel and Ward 1996; Wydoski and Wick 1998). Crowl et al. (1998a) reported that concentrations of nutrients and dissolved organic carbon and levels of primary productivity were generally lower in the main-stem Green River than in adjacent floodplain habitats in the Jensen and Ouray areas and that flow-through floodplain habitats exported substantial amounts of carbon materials to the river. Stanford et al. (1996) presented a general protocol for restoration of regulated rivers that included “restoring peak flows needed to reconnect and periodically reconfigure channel and floodplain habitats.” The American Fisheries Society adopted a position on floodplain management to “encourage restoration of historic floodplain and upland wetlands” (Rasmussen 1996). Restoring access to these warm and productive habitats, which serve as growth and conditioning areas, appears critical for recovery of self-sustaining razorback sucker populations.

Reestablishment of some river-floodplain connections by breaching levees along the middle Green River has been initiated by the Colorado River Recovery Program (Lentsch et al. 1996a). Also, the responses of native and nonnative fish populations to inundation of terrace or depression floodplain habitats are being assessed (Crowl et al. 1998b). However, substantial increases in the spatial extent of floodplain inundation and in the duration of river-floodplain connectivity will also require management of spring-peak releases from Flaming Gorge Dam in high-flow years to provide the magnitude and duration of flows necessary for overbank flooding. Wick (1997) recommended that peak releases from Flaming Gorge Dam be closely coordinated with forecasts of spring runoff for the Yampa River and that, in wet hydrologic cycles, bypass releases from Flaming Gorge Dam in successive years be timed to support and build on Yampa River peak and immediate post-peak flows to reduce sedimentation of spawning substrates and flood nursery habitats at the appropriate time.

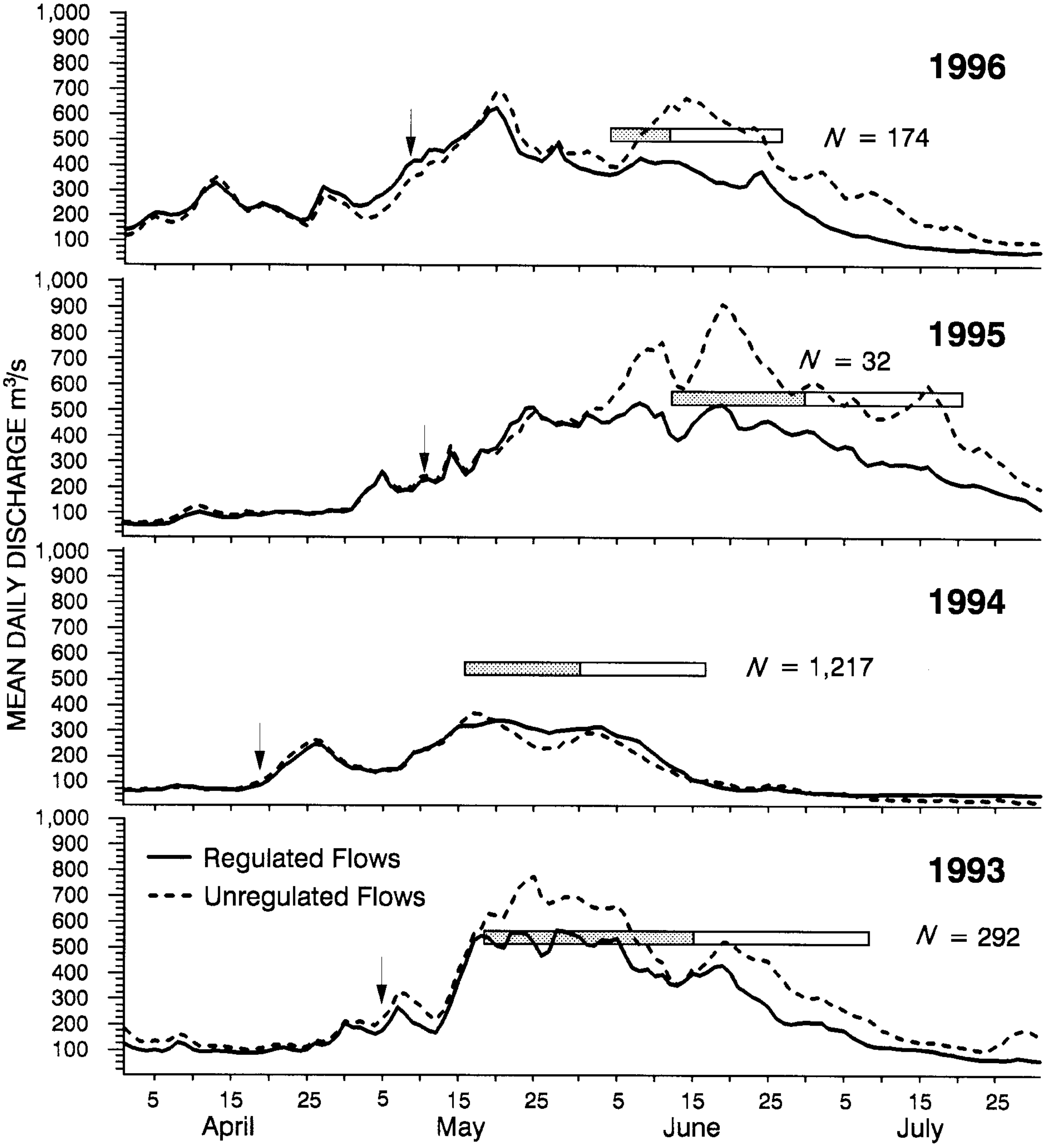
In Reach 2, under existing conditions at Ouray NWR with constructed levees in place, the amount of floodplain inundation begins to increase rapidly at flows of about 527 m^3/s (Section 3.6.5). In Reach 3, floodplain inundation with existing levees begins at flows of about 623 m^3/s in the upper portion between the White River and the upper end of Desolation Canyon, and it begins at flows of about 1,100 m^3/s in lower sections in Canyonlands National Park (Section 3.6.5).

Further, the timing of overbank flooding must be matched with occurrence of razorback sucker larvae in the river (Modde 1997). Muth et al. (1998) estimated that in most years during 1993–1996, larval razorback suckers in the Green River were first captured 20–30 d after initiation of flow, which generally coincided with a relatively steep and consistent increase in flow associated with the beginning of spring runoff. Numbers of larvae collected usually peaked by early or mid-June each year, within 2–4 weeks after initial captures (Figure 4.8). Gauged flows in Reach 2 at Jensen during 1993–1996 exceeded the 527-m^3/s threshold for overbank flooding briefly in 1993 and 1996, but timing of peak flows was matched with the initial occurrence of larval razorback suckers in the river only in 1993 (Figure 4.8).

Under the present regulated flow regime, nursery habitats for razorback sucker larvae in the middle Green River during 1993–1996 were limited primarily to ephemeral shoreline embayments (e.g., backwaters); off-channel habitats such as ponded lower portions of flooded tributary streams, side canals, or channels; and floodplain sites that connect to the main channel at flows less than 527 m^3/s (Section 3.6.5). The off-channel habitats persisted at flows greater than 100 m^3/s in the Jensen and Ouray areas (R. T. Muth, personal observation) and in similar habitats in the Millard Canyon and Anderson Bottom areas of the lower Green River in Canyonlands National Park flood at flows greater than 200 m^3/s (Section 3.6.5). However, with unregulated flows, substantial expanses of floodplain habitat in Reach 2 (Figure 3.16) would have been available to many of the larval razorback suckers produced in 1993, 1995, and 1996 (Figure 4.8). Muth et al. (1998) reported that in the absence of extensive overbank flooding, razorback sucker larvae apparently disappeared from Green River nursery habitats by early or mid-July each year during 1992–1996, suggesting extremely low survival.

4.3.6.2 Summer and Autumn

Recruitment failure of razorback suckers appears to occur in late spring through summer; the failure has been attributed to predation by nonnative fishes. The suspected high mortality of larval razorback suckers in Green River nursery habitats during 1992–1996 may have been due to low growth rates and the concomitant effects of size-dependent processes on survival. Enhanced growth of young in warm and productive floodplain habitats inundated by spring peak flows (Table 4.5) may increase overall survival by shortening the period of vulnerability to predation. Crowl et al. (1998a) reported that floodplain depression ponds along the middle Green River in the Jensen and Ouray areas acted as carbon sinks and were more productive than flow-through



Arrows denote estimated earliest date of spawning in each year. Larval razorback sucker captures denoted by horizontal bar drawn at 527 m^3/s (with existing levees, floodplain inundation in the Ouray portion of Reach 2 increases rapidly at flows higher than 527 m^3/s). Shaded portion of horizontal bar indicates period over which at least the first 50% of all larval razorback sucker captures (*N*) occurred. Flows were measured at the USGS stream gage near Jensen, Utah.

Figure 4.8.—Razorback sucker spawning and larval razorback sucker captures as related to regulated and unregulated flows in Reach 2 of the Green River in Utah and Colorado, 1993–1996. Source: Muth et al. (1998)

floodplain habitats (e.g., terraces). Floodplain depressions should provide an adequate duration of time for young razorback suckers to attain sizes large enough to escape predation by many nonnative fishes in one or two growing seasons (Wydoski and Wick 1998). Age-1 razorback suckers stocked in three floodplain depressions adjacent to the middle Green River in April 1999 appeared to be "thriving" in the presence of abundant nonnative fishes as suggested by autumn sampling of these habitats (Christopherson et al. 1999). Razorback suckers in all three depressions had tripled in size between stocking and recapture, averaging 1.3 mm growth (TL increment) per day. Ongoing research is addressing another factor that potentially limits the survival of larval razorback suckers in existing nursery habitats: the adverse biological effects of selenium contamination (Hamilton et al. 1998).

All of the six early juvenile razorback suckers caught in riverine habitats on the Green River since 1990 were collected from backwaters. Although not necessarily providing conditions believed optimal for growth and survival of young razorback suckers, backwaters and other low-velocity shoreline embayments may serve a role as nursery habitats for the species, especially in areas lacking substantial floodplain habitat (see flows to maximize the quantity and quality of backwaters for Colorado pikeminnow, Section 4.2). High or very high spring flows, and summer conditions resulting from higher spring flows, may improve conditions for young razorback suckers in low-velocity shoreline habitats by reducing the abundance of nonnative cyprinids, which are potential competitors or predators (Section 4.1.2).

4.3.6.3 Winter

Tyus and Karp (1991) concluded that high winter flows flood low-velocity habitats used by overwintering adult razorback suckers and that fluctuating winter flows, particularly those associated with buildup and transport of ice, may induce greater fish movement and stress. Although the effects of this increased movement and energy expenditure on survival, growth, and reproductive potential are unknown (Valdez and Masslich 1989), Tyus and Karp (1991) noted the early spring spawning of razorback suckers suggests that winter-habitat conditions may affect gonad maturation and spawning success. They considered low, stable winter flows as habitat requirements of razorback sucker.

Table 4.6.—Summary of flow and temperature needs of razorback sucker in the Green River system, Utah and Colorado.

Season	River Reach[a]		
	1	2	3
Spring	● Onset of releases from Flaming Gorge Dam closely coordinated with forecasts of spring-runoff flows for the Yampa River (timed to supplement Yampa River peak and immediate post-peak flows) to provide flows compatible with requirements in Reaches 2 and 3.	● Increasing flows associated with the beginning of spring runoff to initiate movements of adults to spawning areas and trigger reproduction (typically begins in April to early May); rate of increase does not appear critical. ● Water temperatures 12–20ºC to provide suitable hatching temperatures for embryos. ● Peak flows coincident with Yampa River peak and immediate post-peak flows to reduce sediment deposition on spawning substrates and to flood nursery habitats. ● Inundation of floodplain habitats in the Jensen and Ouray areas to provide warm, food-rich environments for growth and conditioning of all life stages and to reestablish river-floodplain connections for restoration of the ecosystem. Inundation timed to coincide with occurrence of larvae in the river. – Overbank flooding with existing levees: flows greater than 527 m^3/s for at least 2 weeks. ● Flows greater than 100 m^3/s flood off-channel habitats (e.g., tributary mouths and side canals and channels) in the Jensen and Ouray areas.	● Increasing flows associated with the beginning of spring runoff to initiate movements of adults to spawning areas and trigger reproduction (typically begins in April); rate of increase does not appear critical. ● Water temperatures 12–20ºC to provide suitable hatching temperatures for embryos. ● Inundation of floodplain habitats between the White River and upper end of Desolation Canyon and in Canyonlands National Park to provide warm, food-rich environments for growth and conditioning of all life stages and to reestablish river-floodplain connections for restoration of the ecosystem. Inundation timed to coincide with occurrence of larvae in the river. – Overbank flooding with existing levees between the White River and upper end of Desolation Canyon: flows greater than 623 m^3/s for at least 2 weeks. – Overbank flooding with existing levees in Canyonlands National Park: flows greater than 1,100 m^3/s for at least 2 weeks. ● Flows greater than 200 m^3/s flood off-channel habitats (e.g., tributary mouths, washes, and side canyons) in the Millard Canyon and Anderson Bottom areas in Canyonlands National Park.

Table 4.6.—Continued.

Season	River Reach[a]		
	1	2	3
Spring (continued)		● Flows that transport sediment and build in-channel sandbars for backwater nursery habitat. Occasional high flows to build high sandbars, scour encroaching riparian vegetation, and maintain habitat complexity. ● Occasional high flows that reduce the abundance of nonnative fishes in low-velocity shoreline habitats (e.g., backwaters).	● Flows that transport sediment and build in-channel sandbars for backwater nursery habitat. Occasional high flows to build high sandbars, scour encroaching riparian vegetation, and maintain habitat complexity. ● Occasional high flows that reduce the abundance of nonnative fishes in low-velocity shoreline habitats (e.g., backwaters).
Summer/ Autumn	● Releases from Flaming Gorge Dam to provide flows compatible with requirements in Reaches 2 and 3.	● Sustained inundation of floodplain depression ponds throughout the growing season (possibly over winter) probably favorable; not necessarily related to river flows during the period, but successive years of spring overbank flooding may be needed to provide overwintered fish return access to the main channel. ● Flows that decline in late spring to mid-summer to low, relatively stable base flows. Reduces the length of time between end of overbank flooding and start of backwater development (period when availability of in-channel low-velocity habitats is limited) and permits earlier colonization of backwaters by invertebrates.	● Sustained inundation of floodplain depression ponds in floodplain wetlands throughout the growing season (possibly over winter) probably favorable; not necessarily related to river flows during the period, but successive years of spring overbank flooding may be needed to give overwintered fish access to return to the main channel. ● Flows that decline in late spring to mid-summer to low, relatively stable base flows. Reduces the length of time between end of overbank flooding and start of backwater development (period when availability of in-channel low-velocity habitats is limited) and permits earlier colonization of backwaters by invertebrates.

Table 4.6.—Continued.

Season	River Reach[a]		
	1	2	3
Summer/ Autumn (continued)		● Flows that provide for relatively stable backwater nursery habitats to enhance invertebrate productivity and the overall quality of backwaters.	● Flows that provide for relatively stable backwater nursery habitats to enhance invertebrate productivity and the overall quality of backwaters.
Winter	● Releases from Flaming Gorge Dam to provide flows compatible with requirements in Reaches 2 and 3.	● Low, relatively stable flows to prevent flooding of low-velocity habitats and reduce the likelihood of increased movements of adults caused by ice breakup and transport.	● Low, relatively stable flows to prevent flooding of low-velocity habitats.

[a] River reaches: (1) Flaming Gorge Dam to Yampa River confluence, (2) Yampa River confluence to White River confluence, and (3) White River confluence to Colorado River confluence.

4.4 HUMPBACK CHUB

4.4.1 Distribution and Status Overview

The endangered humpback chub is endemic to the Colorado River basin, with ancestral fossil evidence of a *Gila* complex dating back to the Miocene epoch (Miller 1955). *Gila cypha* is believed to be a more recent, specialized derivative that evolved in response to conditions in large, erosive Colorado River habitats during the mid-Pliocene and early Pleistocene epochs, 3–5 million years ago (Minckley et al. 1986).

Historic abundance of the humpback chub is unknown, and information on historic distribution is incomplete (Tyus 1998). There are several reasons for deficiencies in historic records of humpback chubs. The species occurs primarily in relatively inaccessible canyon areas and was rare in most early collections (Tyus 1998). Accurate early assessments of distribution and abundance were hampered by uncertainties regarding the taxonomy and nomenclature of species in the genus *Gila*. For example, during the 1950s, two forms of bonytail (a common name for morphotypes of the Colorado River *Gila* complex) were taxonomically recognized as subspecies, roundtail chub *Gila robusta robusta* and bonytail chub *Gila robusta elegans*. A third form, *Gila cypha*, had only recently been described by Miller (1946) and was not universally considered a valid taxon (Holden and Stalnaker 1970; Holden 1991). Although many researchers recognized the presence of morphological variants, a common nomenclature had not been accepted. As a result, many early fish surveys of the Colorado River system assigned the vernacular “bonytail” to all three closely related *Gila* species (*G. cypha*, *G. elegans*, and *G. robusta*), thereby confounding confirmation of humpback chub localities prior to about 1970 (Banks 1964; Vanicek and Kramer 1969; Holden and Stalnaker 1970; Valdez and Clemmer 1982; Douglas et al. 1989; Rosenfeld and Wilkinson 1989; Minckley 1991; Dowling and DeMarais 1993; Quarterone 1993). Also, human alterations of rivers throughout the Colorado River basin prior to fish surveys may have depleted or eliminated the humpback chub from some river reaches before its occurrence was documented. Despite weaknesses in historic records, evidence exists to suggest that the original range of the species included most canyon-bound reaches of the Colorado River system. Known historic distribution of humpback chubs includes portions of the main-stem Colorado River and four of its tributaries: the Green, Yampa, White, and Little Colorado Rivers (USFWS 1990a).

Present knowledge of the distribution of humpback chubs is based on records from widely separated locations since about 1980. Seven populations or population segments are currently identified for humpback chub (Valdez and Clemmer 1982; USFWS 1990a): (1) Little Colorado River, Arizona; (2) Colorado River in Marble and Grand Canyons, Arizona; (3) Colorado River in Cataract Canyon, Utah; (4) Colorado River in Black Rocks, Colorado; (5) Colorado River in Westwater Canyon, Utah; (6) Green River in Desolation and Gray Canyons, Utah; and (7) Yampa River in Yampa Canyon, Dinosaur National Monument, Colorado.

The largest and most stable extant humpback chub population is thought to reside in the lower Colorado River basin in the Little Colorado and main-stem Colorado Rivers near their confluence in Marble and Grand Canyons, Arizona. Valdez and Ryel (1995) estimated that 3,750 adult humpback chubs larger than 200 mm TL occurred in the main-stem Colorado River during 1990–1993. Douglas and Marsh (1996) reported 4,346 humpback chubs larger than 150 mm TL in the Little Colorado River in 1992.

In the upper Colorado River basin, populations of humpback chub occur in Cataract Canyon (Valdez 1990; Valdez and Williams 1993), Black Rocks (Kaeding et al. 1990), Westwater Canyon (Chart and Lentsch 1999), Desolation and Gray Canyons (Chart and Lentsch 2000), and Yampa Canyon (Karp and Tyus 2000). Occupied sections of these canyon-bound reaches range in length from 3.7 km (Black Rocks) to 93.3 km (Desolation and Gray Canyons). Humpback chubs are distributed throughout most of Black Rocks and Westwater Canyon (12.9 km) and in or near whitewater reaches of Cataract Canyon (19.3 km), Desolation and Gray Canyons, and Yampa Canyon (73.6 km). A few humpback chubs also have been reported from the Green River in Dinosaur National Monument, primarily in Whirlpool Canyon (Holden and Stalnaker 1975a; Karp and Tyus 1990b) and Split Mountain Canyon (Vanicek 1967; Holden and Stalnaker 1975a); from the Yampa River in Cross Mountain Canyon (Wick et al. 1981); and from the Little Snake River about 10 km upstream of its confluence with the Yampa River (Hawkins et al. 1996).

Reliable population estimates for humpback chubs in the upper basin have been difficult to obtain because of low recapture rates. Chart and Lentsch (1999) sampled for humpback chubs at three locations in Westwater Canyon during 1993–1996 and derived site-specific mean annual abundance estimates ranging from 572 to 5,880 for individuals larger than 175 mm TL. However, confidence intervals about the estimates were typically greater than the means. Pfeifer et al. (1998) estimated a mean population size of 1,528 (95% confidence interval, 888–2,750) for adult humpback chubs in Black Rocks. Abundance estimates for adult humpback chubs in other upper basin populations are based on substantially less data and include: 500 in Cataract Canyon (Valdez 1990), 600 in Yampa Canyon (estimated by T. P. Nesler, Colorado Division of Wildlife, from data provided in Karp and Tyus 1990b), and 1,500 in Desolation and Gray Canyons (estimated by R. A. Valdez from data provided in Chart and Lentsch 2000).

The humpback chub was designated as endangered before enactment of the 1973 Endangered Species Act, and a formal listing package with identified threats was never assembled. Although habitat losses were documented (e.g., Miller 1961), data on historic abundance and distribution of humpback chubs were limited, and threats to the species poorly understood. Threats were first identified in the Humpback Chub Recovery Plan (USFWS 1990a), which concluded that decline of the humpback chub may be due to a combination of factors, including alteration of river habitats by dams, irrigation, dewatering, and channelization; competition with and predation by nonnative fishes; hybridization with other *Gila*; and other factors such as changes in food resources resulting from stream alterations, pesticides and pollutants, and parasitism. Critical habitat designated for humpback chub makes up about 28% of the species' original range and occurs in both the upper and lower Colorado River basins (USFWS 1994). River reaches of critical habitat for humpback chub in the Green River system include the Yampa River within Dinosaur National Monument, Green River from its confluence with the Yampa River downstream to the southern boundary of Dinosaur National Monument, and Green River within Desolation and Gray Canyons.

4.4.2 Life History Overview

The humpback chub evolved in seasonally warm and turbid water and is highly adapted to the unpredictable hydrologic conditions that occurred in the pristine Colorado River system. It is specialized for life in torrential water, with an enlarged stabilizing nuchal hump and large falcate fins (Minckley 1991). Although not strong swimmers (Bulkley et al. 1982), humpback chubs are apparently so well adapted to canyon environments that populations appear to have always occupied a specialized niche in canyon-bound segments of the river system (Carlson and Muth 1989), where individual adults exhibit high fidelity to particular locales (Valdez and Clemmer 1982; Valdez and Ryel 1995). Adults are thought to be negatively phototatic and are more active in turbid water or at night (Valdez et al. 1992; Valdez and Ryel 1995, 1997). The humpback chub is an obligate warm-water fish that requires relatively warm temperatures for spawning, egg incubation, and survival of larvae. Optimum growth temperatures range from 16 to 22°C (Hamman 1982; Lechleitner 1992). Little else is known about reproduction except that spawning occurs on the descending limb of annual spring hydrographs, most likely over cobble or gravel substrates (Valdez and Clemmer 1982; Valdez et al. 1982; Kaeding and Zimmerman 1983; Tyus and Karp 1989; Valdez and Ryel 1995).

Unlike larvae of Colorado pikeminnow and razorback sucker, emerging humpback chub larvae do not appear to drift extensively but instead remain in the general vicinity of spawning areas. Sampling for larvae and YOY immediately downstream of Black Rocks and Westwater Canyon yielded very low numbers of young humpback chubs (Valdez et al. 1982; Chart and Lentsch 1999). Robinson et al. (1998) documented drift of larval humpback chubs from the Little Colorado River and into the main-stem Colorado River in Grand Canyon, but they noted lower abundance at more downstream stations and suggested that humpback chub larvae may drift shorter distances than larvae of other native fishes (e.g., speckled dace, bluehead sucker, and flannelmouth sucker). Humpback chubs mature in 2–3 years at approximately 200 mm TL and may live 20–30 years (Valdez et al. 1992; Hendrickson 1993).

The diet of humpback chubs in the upper basin has not been fully described. Tyus and Minckley (1988) reported that migrating Mormon crickets *Anabrus simplex* were an important food source for humpback chubs in the Green and Yampa Rivers. In the Grand Canyon, humpback chubs primarily consumed aquatic invertebrates (e.g., midges, blackflies, and amphipods), green algae, terrestrial invertebrates, and occasionally fish and reptiles (Kaeding and Zimmerman 1983; Kubly 1990; Valdez and Ryel 1997).

Two species of nonnative parasites infect humpback chubs. The external parasitic copepod (*Lernaea cyprinacea*) has been reported from all populations (Valdez et al. 1982), and the internal Asian tapeworm *Bothriocephalus acheilognathi* is found in humpback chubs of the Grand Canyon

(Brouder and Hoffnagle 1997; Clarkson et al. 1997). Infection by the Asian tapeworm may cause stress or death to the host, and widespread infestation may occur during periods of stress. This parasite can complete its life cycle only where water temperatures are greater than 20°C but is apparently able to survive in a fish host at colder temperatures.

4.4.3 Research on Humpback Chub for the 1992 Flaming Gorge Biological Opinion

One investigation conducted in support of the 1992 Biological Opinion on Operation of Flaming Gorge Dam focused on humpback chub (Table 1.1). That study ("Habitat use, spawning and species associations of humpback chub, *Gila cypha*, in the Yampa and Green Rivers, Dinosaur National Monument, Colorado and Utah") evaluated the ecology and life history of humpback chub in the Yampa and Green Rivers, Dinosaur National Monument, from 1986 to 1989. Results of that study (Tyus and Minckley 1988; Karp and Tyus 1990b) were used to identify habitat and flow needs of humpback chubs in the Green River (Tyus and Karp 1989) and to develop overall flow recommendations for the Green River (USFWS 1992).

4.4.4 Research on Humpback Chub for the 1990–1996 Flaming Gorge Flow Recommendations Investigation

The humpback chub was the least intensively studied of the extant endangered fishes included in the Flaming Gorge Flow Recommendations Investigation. Several factors hampered research on humpback chubs and complicated an understanding of the species' life history and flow needs in the Green River. Its limited distribution and rarity, when compared with the Colorado pikeminnow and razorback sucker, resulted in small sample sizes, making it difficult to interpret results. In addition, the potential presence of all three chub species and their intergrades in Desolation and Gray Canyons confounded species-specific interpretations of results, particularly for younger life stages (Chart and Lentsch 2000; T. E. Dowling, Arizona State University, personal communication). Douglas et al. (1998) noted that application of several discriminating adult characteristics (as in ISMP protocol) may not be sufficient to distinguish among juveniles of these species in the field. Researchers were, in fact, unable to reliably differentiate any YOY and juvenile chubs to the species level (T. E. Chart, Utah Division of Wildlife Resources, personal communication). As a result, studies generally classified juvenile and smaller specimens and a number of larger specimens as *Gila* spp. It should be noted, however, that although studies conducted in Desolation and Gray Canyons as part of the Flaming Gorge Flow Recommendations Investigation reported *Gila* spp., humpback chubs were the most commonly collected adult *Gila* (Chart and Lentsch 2000).

Studies on *Gila* conducted during the Flaming Gorge Flow Recommendations Investigation primarily addressed research questions dealing with seasonal relationships between life-history stages and flow-habitat conditions. Three studies were conducted in Desolation and Gray Canyons. Chart and Lentsch (2000) monitored the fish community and detailed aspects of the ecology and life history of *Gila*, including humpback chub. Day et al. (2000) reported on backwater use by YOY *Gila*, and Orchard and Schmidt (2000) conducted a geomorphic assessment of Desolation and Gray Canyons to estimate the availability of potential humpback chub habitats.

4.4.5 Other Recent Research on Humpback Chub

Because of the limited amount of information that has been gathered on the relatively small humpback chub populations in the Green and Yampa Rivers, data from other recent studies and data-integration projects were utilized to supplement information on the species. These studies dealt primarily with general aspects of the life history and ecology of the humpback chub but also examined effects of flows. These studies evaluated humpback chub populations in the Grand Canyon (Valdez and Ryel 1995, 1997; Valdez and Carothers 1998) and in Westwater Canyon (Chart and Lentsch 1999). Additional literature was also included as appropriate.

4.4.6 Ecology of Humpback Chub in the Green River System

4.4.6.1 Distribution and Abundance

Before Flaming Gorge Dam.**—**Failure to recognize *Gila cypha* as a species until 1946 complicated interpretation of historic distribution of humpback chubs in the Green River (Douglas et al. 1989, 1998). The best available information, however, suggests that before Flaming Gorge Dam, humpback chubs were distributed in canyon regions throughout much of the Green River, from the present site of Flaming Gorge Reservoir downstream through Desolation and Gray Canyons (Vanicek 1967; Holden and Stalnaker 1975a; Holden 1991). In addition, the species occurred in the Yampa and White Rivers. The closely related bonytail (*Gila elegans)* also appears to have been common in the Green River from Labyrinth and Stillwater Canyons upstream to the present-day location of Flaming Gorge Reservoir (Bosley 1960; Holden and Stalnaker 1975a). Pre-impoundment surveys of the Flaming Gorge Reservoir basin were conducted between 1958 and 1960 by the Utah Department of Fish and Game and Wyoming Game and Fish Department (Bosley 1960; Gaufin et al. 1960; McDonald and Dotson 1960; Smith 1960). Discrepancies exist over the numbers and species of fishes collected. However, photographic evidence and written descriptions leave little doubt that humpback chubs were present in the upper Green River. Smith (1960) reported both humpback chubs and bonytails in July 1959 from the Green River near Hideout Canyon, which is now inundated by Flaming Gorge Reservoir. McDonald and Dotson (1960) reported only bonytails in collections from Hideout Canyon, but they acknowledged that several morphological variants existed within the group. Bosley (1960) conducted a survey of the Green River from its upper reaches to near the dam site and recorded all chubs collected as bonytail, even though he stated that "there appears to be a change in the physical characteristics of this fish in the extreme lower sections of the study area" and presented photographs that clearly included all three forms of *Gila* (Holden 1991).

Additional locations in the main-stem Green River at which humpback chubs were documented before and soon after closure of Flaming Gorge Dam include Whirlpool, Split Mountain, Desolation, and Gray Canyons (Vanicek 1967; Holden and Stalnaker 1975a; Karp and Tyus 1990b; P. B. Holden, BIO/WEST, Inc., personal communication).

Tributaries to the Green River for which historic collection records exist include the Yampa and White Rivers. Tyus (1998) verified the presence of seven humpback chubs in collections of the University of Colorado Museum that were collected from the Yampa River in Castle Park between 19 June and 11 July 1948. A single humpback chub was found in the White River near Bonanza, Utah, in June 1981 (Miller et al. 1982b), and a possible bonytail-humpback chub intergrade was also captured in the White River in July 1978 (Lanigan and Berry 1981).

After Flaming Gorge Dam.—Present distribution of humpback chubs in the Green River (Figure 4.9) includes Whirlpool and Split Mountain Canyons (109–145 km downstream from Flaming Gorge Dam), and a reproducing population can be found in Desolation and Gray Canyons (360–426 km downstream from Flaming Gorge Dam). The Green River in Whirlpool Canyon was last sampled during 1986–1989 by Karp and Tyus (1990b), and three humpback chubs were captured. Recent opportunistic collections in Whirlpool and Split Mountain Canyons failed to yield additional specimens. However, no systematic efforts have been made to collect humpback chubs from these canyons in recent years, and the species likely persists in these areas (T. Modde, U.S. Fish and Wildlife Service, personal communication). The Utah Division of Wildlife Resources has monitored the fish community in Desolation and Gray Canyons since 1989 and has consistently reported captures of age-0, juvenile, and adult *Gila* (including humpback chub), indicating a reproducing population (Chart and Lentsch 2000).

The Yampa River is the only tributary to the Green River presently known to support a reproducing humpback chub population. Between 1986 and 1989, Karp and Tyus (1990b) collected 130 humpback chubs from Yampa Canyon and indicated that a small but reproducing population was present. Continuing captures of juveniles and adults within Dinosaur National Monument indicate that a population persists in Yampa Canyon (T. Modde, U.S. Fish and Wildlife Service, personal communication). Small numbers of humpback chubs also have been reported in Cross Mountain Canyon on the Yampa River and in the Little Snake River about 10 km upstream of its confluence with the Yampa River (Wick et al. 1981; Hawkins et al. 1996). The Yampa River population is located above the confluence with the Green River and is not directly affected by Green River flows.

Closure and operation of Flaming Gorge Dam had an immediate effect on temperature and flow regimes of the Green River (especially in Reach 1; Figure 2.1), which, along with a fish eradication project (Holden 1991), resulted in major changes in the downstream fish community (Section 4.1.1). The distribution and abundance of humpback chubs and bonytails were particularly affected. The disappearance of humpback chubs and bonytails from Reach 1 coincided with the poisoning of the Green River, filling of the reservoir, and subsequent regulation of the river in the early to mid-1960s. During the same period, humpback chubs continued to reproduce and recruit in

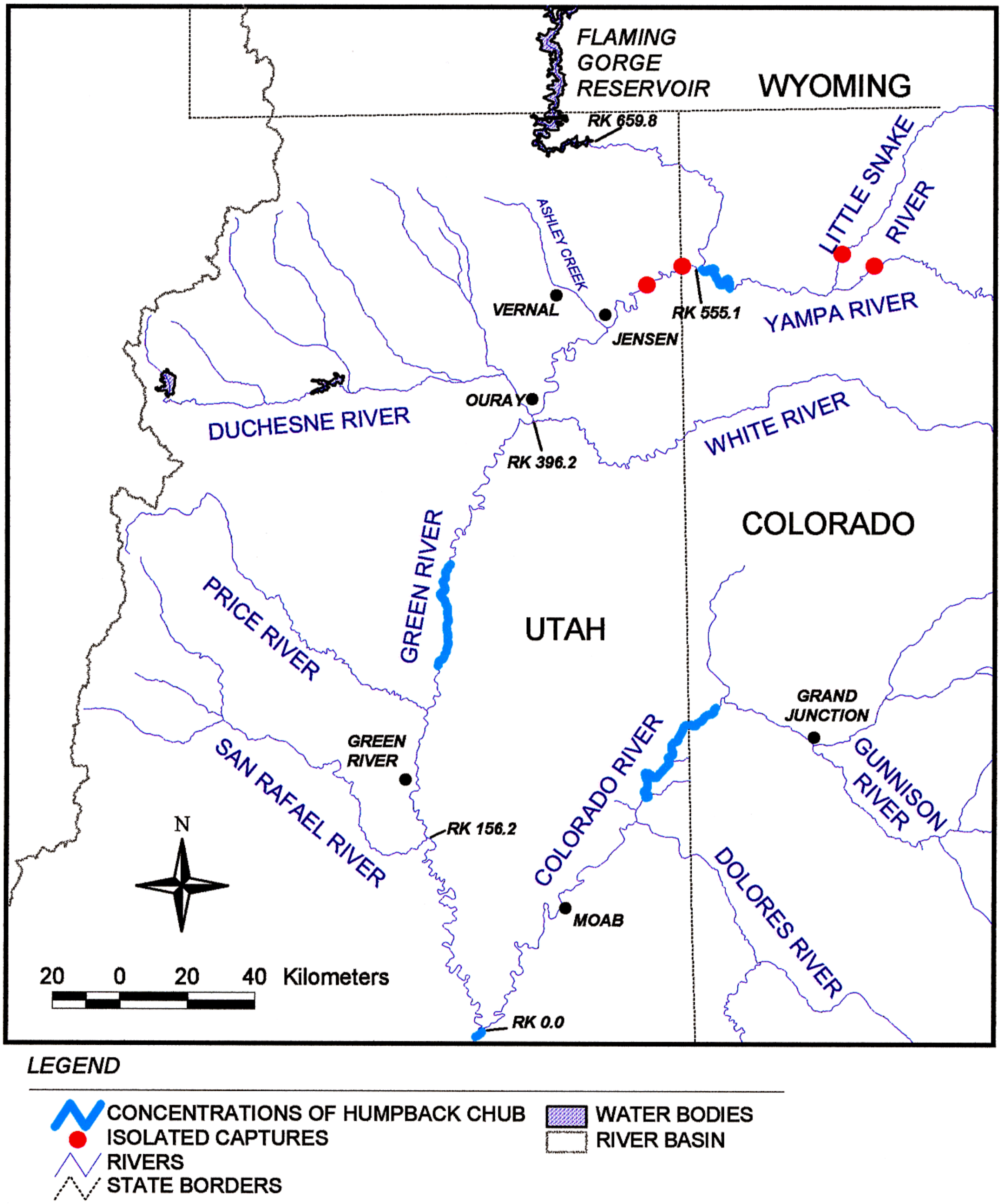


Figure 4.9.—Present distribution of humpback chub in the upper Colorado River basin.

the unregulated Yampa River and in Desolation and Gray Canyons on the lower Green River, with its somewhat modified flow regimes but essentially natural temperature regime (Section 3.5.1.3).

4.4.6.2 Life History by Season

4.4.6.2.1 Spring

4.4.6.2.1.1 Reproduction

Adult movements.—Unlike Colorado pikeminnow and razorback sucker, humpback chubs in the Green River do not appear to make long-distance spawning migrations in the river (Karp and Tyus 1990b). Radiotelemetry and tagging studies on other humpback chub populations have revealed strong fidelity by adults for specific locations, with little movement to areas outside of home-canyon regions. Humpback chubs in Black Rocks (Valdez and Clemmer 1982), Westwater Canyon (Chart and Lentsch 1999), and Desolation and Gray Canyons (Chart and Lentsch 2000) do not exhibit spawning migrations. Mean maximum displacement in Black Rocks was 0.8 km for radio-tagged adults older than 3 months and 1.67 km for Carlin-tagged adults older than 1–12 months (Valdez and Clemmer 1982). Kaeding et al. (1990) reported maximum displacement of radio-tagged adults in Black Rocks of 1.4 km. The greatest movements and only documented spawning migrations by humpback chubs occur in the Grand Canyon, where adults annually move from the main-stem Colorado River, which is cooled by hypolimnetic releases from Glen Canyon Dam, and into the seasonally warmed Little Colorado River to spawn (Valdez and Ryel 1995, 1997; Valdez and Carothers 1998). The greatest round-trip spawning movement recorded for a humpback chub between the main-stem Colorado River and the Little Colorado River was about 20 km. Data from 92 humpback chubs marked with Carlin or Floy tags and at large for an average of 2,990 d (range of 304–4,496 d) showed average distance from original capture to recapture of 4.29 km (range of 0.1–14.4 km), revealing remarkable fidelity for specific river locales over periods of years. No differences between males and females were reported in spawning-related movements (Valdez and Carothers 1998).

Spawning periods and associated river flows and temperatures.—In the Green River and upper Colorado River, humpback chubs spawn in spring and summer, as flows decline after the spring peak (Valdez and Clemmer 1982; Valdez et al. 1982; Kaeding and Zimmerman 1983; Tyus and Karp 1989; Karp and Tyus 1990b; Chart and Lentsch 1999, 2000). Similar spawning patterns were reported from the Grand Canyon (Kaeding and Zimmerman 1983; Valdez and Ryel 1995, 1997). Tyus and Karp (1991) found that in the Yampa and Green Rivers in Dinosaur National Monument, humpback chubs spawn during spring and early summer, following peak flows at water temperatures of about 20°C. They estimated that the spawning period for humpback chubs ranged from May into July, with spawning occurring earlier in low-flow years and later in high-flow years; spawning was thought to occur only during a 4–5 week period (Karp and Tyus 1990b).

Chart and Lentsch (2000) estimated hatching dates from back-calculated lengths of young *Gila* caught in Desolation and Gray Canyons on the Green River between 1992 and 1995. They determined that hatching occurred on the descending limb of the hydrograph as early as 7 June in 1994 at a flow of 283 m^3/s (USGS gage near Green River, Utah) and as late as 1 July in 1995 at a flow of 731 m^3/s. For this report, we estimated dates of peak spawning for *Gila* in Desolation and Gray Canyons during 1992–1995 by subtracting the mean incubation time (6 d) of fertilized *Gila* eggs at 19–20^{o}C (Marsh 1985; Muth et al. 1985; Muth 1990) from the peak hatching dates estimated by Chart and Lentsch (2000). Peak spawning and hatching dates were associated with instantaneous daily main-channel water temperatures measured at the USGS gage near Green River, Utah (Table 4.7).

In a much larger set of collections from Westwater Canyon, Chart and Lentsch (1999) estimated hatching dates of young *Gila* on the basis of back-calculated lengths of 521 age-0 chubs collected between 1992 and 1996. These estimated hatching dates were used to estimate peak spawning dates for *Gila* in Westwater Canyon during 1992–1996 by the same method described above for *Gila* in Desolation and Gray Canyons. Peak spawning and hatching dates were associated with maximum main-channel daily water temperatures measured at the USGS gage near the Colorado-Utah state line (Table 4.8). These estimated peak spawning and hatching dates are believed to represent humpback chubs in Westwater Canyon, because the majority of adult *Gila* collected from Westwater Canyon were identified as humpback chub.

Estimated dates of peak spawning and hatching activity for 1992–1996 (Table 4.8) associated with maximum daily main-channel water temperatures and mean daily flows for the study period are shown in Figures 4.10 and 4.11, respectively. Spawning of *Gila* in Westwater Canyon appears to be strongly influenced by temperature, as indicated by the consistent results between 1992 and 1996. During those years, peak spawning occurred during a relatively narrow range of water temperatures, whereas flows at the time of estimated peak spawning were widely variable, ranging

Table 4.7.—Estimated peak hatching and spawning dates for *Gila* in Desolation and Gray Canyons on the Green River, Utah, and associated instantaneous daily main-channel water temperatures measured at the USGS gage near Green River, Utah, 1992–1996.

Estimated Peak Hatching Dates	Temperature (°C) on Peak Hatching Dates	Estimated Peak Spawning Dates	Temperature (°C) on Peak Spawning Dates
9 June 1992	22	3 June 1992	21
21 June 1993	21	15 June 1993	22
7 June 1994	20	1 June 1994	20
1 July 1995	20	26 June 1995	21

Source: Chart and Lentsch (2000).

Table 4.8.—Estimated peak hatching and spawning dates for humpback chubs in Westwater Canyon on the Colorado River, Utah, and associated maximum daily main-channel water temperatures measured at the USGS gage near the Colorado-Utah state line, 1992–1996.

Estimated Peak Hatching Dates	Temperature (°C) on Peak Hatching Dates	Estimated Peak Spawning Dates	Temperature (°C) on Peak Spawning Dates
19 June 1992	Not available	13 June 1992	Not available
29 June 1992	Not available	23 June 1992	Not available
13 July 1993	19.8	7 July 1993	17.1
20 June 1994	21.0	14 June 1994	19.4
5 August 1995	20.3	31 July 1995	19.3
5 July 1996	20.9	30 June 1996	18.1
10 July 1996	21.0	4 July 1996	20.9

Source: Chart and Lentsch (1999).

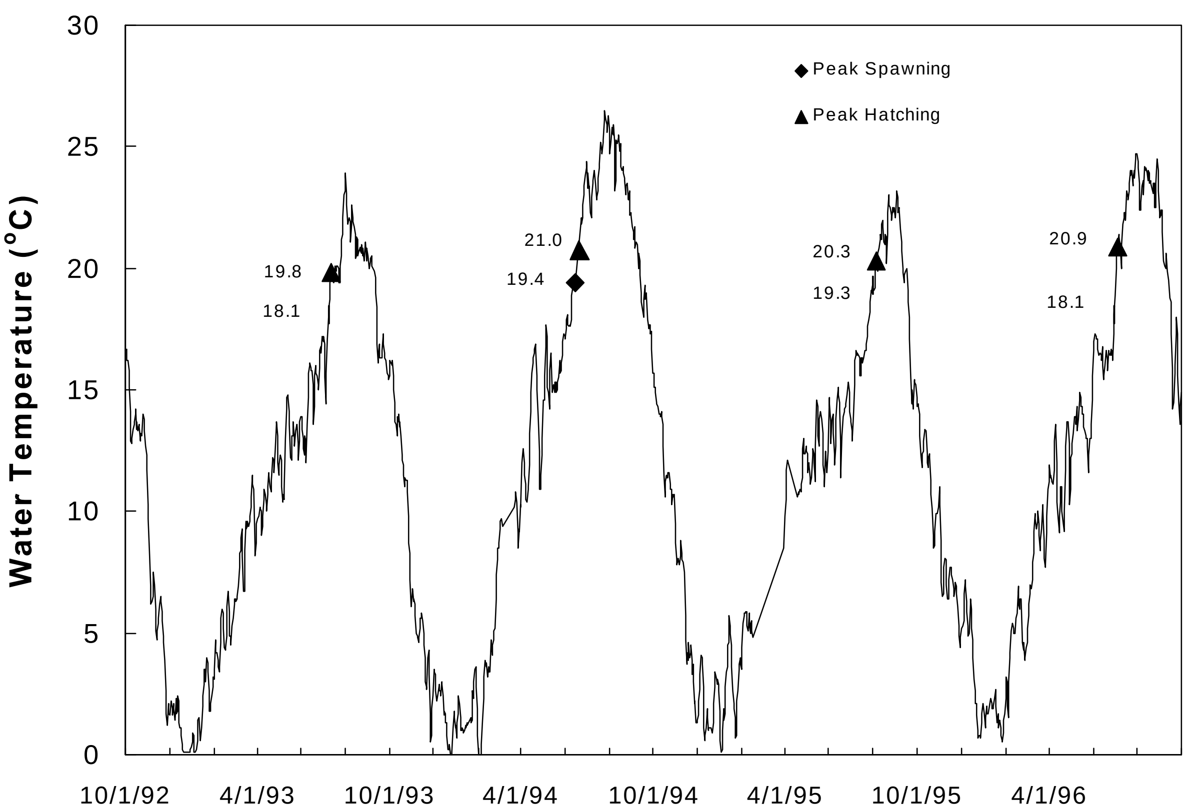


Figure 4.10.—Relationships between estimated peak spawning and hatching of humpback chubs and maximum daily main-channel water temperatures in Westwater Canyon, Colorado River, Utah. Source: Chart and Lentsch (1999)

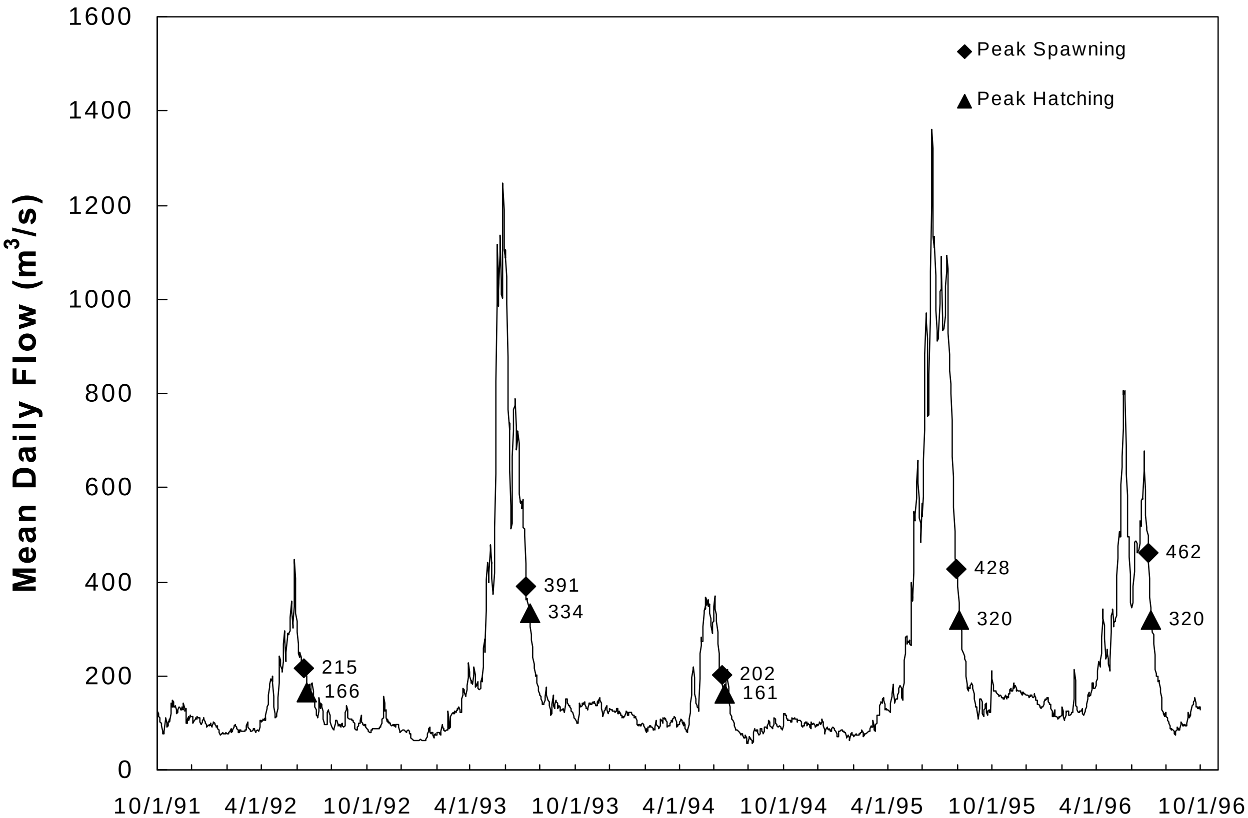


Figure 4.11.—Relationships between estimated peak spawning and hatching of humpback chubs and mean daily flows in Westwater Canyon, Colorado River, Utah. Source: Chart and Lentsch (1999)

from 166 to 461 m^3/s. The date of peak spawning also varied considerably, from 19 June to 5 August, and it was later in the higher water years with colder water. Similar to the Green River peak spawning, peak spawning in Westwater Canyon occurs on the descending limb of the spring runoff hydrograph at water temperatures of approximately 17 to 21°C. Spawning and hatching temperatures in Desolation and Gray Canyons may be slightly higher than those observed in Westwater Canyon; however, the temperature data sets are not directly comparable, and the Desolation-Gray data set was much smaller than the Westwater data set, thus making it likely that the full range of hatching dates was not documented.

Although definitive relationships have not been established between flow and reproduction and recruitment of YOY *Gila*, Chart (2000) documented increased reproduction and recruitment of *Gila* in Desolation and Gray Canyons during moderate to wet years. Chart (2000) recommended that, during moderate to wet years, peak flows in Desolation and Gray Canyons should be near 708 m^3/s, with the full breadth of the spring-runoff period lasting 60 d or more to benefit *Gila* reproduction.

Spawning activity of the relatively large and well-documented humpback chub population in the Little Colorado River exhibits patterns similar to populations in the upper Colorado River basin, but timing of spawning is earlier in the Little Colorado River. In the Little Colorado River, humpback chub spawning apparently commences during mid-March to mid-April, when mean water temperatures are greater than 14ºC and often while flows remain high. Spawning activities peaked as flows declined to base flow in April (Gorman and Stone 1999).

Habitat use by spawning adults during spring runoff.—Little is known about spawning habitats and behavior of adult humpback chubs during high spring-runoff flows. Habitats where ripe humpback chubs have been collected are typically deep, swift, and turbid. As a result, spawning in the wild has not been directly observed. The humpback chub is a broadcast spawner, presumably over mid-channel cobble or gravel bars, with small (2.5–3.0 mm diameter) semiadhesive eggs that become lodged in the substrate interstices (Hamman 1982). Gorman and Stone (1999) reported that ripe male humpback chubs in the Little Colorado River aggregated in areas of complex habitat structure (i.e., matrix of large boulders and travertine masses combined with chutes, runs, and eddies, 0.5–2.0 m deep) and were associated with deposits of clean gravel. Valdez and Ryel (1995, 1997) reported that during spring, adult humpback chubs in the Colorado River in Grand Canyon primarily used large recirculating eddies, occupying areas of low velocity adjacent to high-velocity currents that deliver food items. They also reported that adults congregated at tributary mouths and flooded side canyons during high flows.

In the upper Colorado River basin during spring runoff, spawning adult humpback chubs appear to utilize cobble bars and shoals adjacent to relatively low-velocity shoreline habitats that are typically described as shoreline eddies (Valdez et al. 1982; Karp and Tyus 1990b; Valdez et al. 1990; Valdez and Ryel 1995, 1997; T. E. Chart, Utah Division of Wildlife Resources, personal communication). Tyus and Karp (1989) reported that humpback chubs in the Yampa River occupy and spawn in or near shoreline eddy habitats. They also hypothesized that spring peak flows were important for reproductive success because availability of these habitats is greatest during spring runoff; loss or reduction of spring peak flows could potentially reduce availability of spawning habitat.

Habitat use by juveniles during spring runoff.—The limited data available on habitat use by juvenile humpback chubs in the upper basin indicate that, like adults, the juveniles utilize shoreline eddies and other low-velocity habitats during the spring runoff (Chart and Lentsch 1999, 2000). In the main-stem Colorado River in the Grand Canyon, juveniles less than 200 mm TL were most abundant along talus and vegetated shorelines as well as debris fans (Valdez and Ryel 1995, 1997; Converse et al. 1998). It was also found in the Grand Canyon that daily inundation and desiccation of shoreline habitats due to fluctuating dam releases caused juvenile humpback chubs to abandon those habitats in search of more permanent environments, possibly exposing them to predation and excessive energy expenditure (Valdez and Ryel 1995; Converse et al. 1998). Fish greater than 175–200 mm TL used large recirculating eddies.

Habitat availability during spring runoff.—Orchard and Schmidt (2000) conducted a geomorphic assessment of humpback chub habitat in Desolation and Gray Canyons at flows ranging from 59 to 764 m^3/s. They found the character of eddy habitats to be strongly influenced by flow, whereas the total amount of eddy area was not. At low flow, the majority of low-velocity habitats occur as large eddies formed by channel constrictions. Eddy habitats tended to increase in frequency and decrease in size from base-flow conditions up to flows of approximately 198 m^3/s. At flows greater than 198 m^3/s, eddies decreased in frequency but increased in size, resulting in essentially no net change in total area but significant differences in the size of individual eddies. Large recirculating eddy habitats were most common at low and high flows.

4.4.6.2.1.2 Embryos

Humpback chubs have a relatively low fecundity rate when compared with cyprinids of similar size (Carlander 1969). Eight humpback chubs (355–406 mm TL) manually stripped of eggs averaged 2,523 ova per fish (Hamman 1982), with an estimated fecundity of 5,262 ova per kilogram of body weight. Eleven humpback chubs from the Little Colorado River yielded 4,831 ova/fish following injections of carp pituitary and field stripping (R. W. Clarkson, Reclamation, unpublished data).

Incubation time is about 115–160 h at near-optimum water temperatures of 19–20°C (Hamman 1982; Miller and Hubert 1990). Hatching success of embryos and survival of larvae are temperature dependent (Hamman 1982; Marsh 1985), with the most successful hatching and survival at temperatures greater than 19–20°C, and highest survival of larvae occurring at 21–22°C (Table 4.9). Hamman (1982) also found that the time from fertilization to hatching ranged from 72 h at 26.0°C to 465 h at 10.0°C, and time from hatching to swim-up varied from 72 h at 21.0–22.0°C to 372 h at 15.0°C. The proportion of abnormal fry varied with temperature, from 17% at 25.0°C to 33% at 15.0°C. Marsh (1985) reported similar results.

Table 4.9.—Relationships between water temperature and hatching success and survival of humpback chub larvae.

Temperature (°C)	% Hatching Success	% Survival of Larvae
12–13	12	15
16–17	62	91
19–20	84	95
21–22	79	99

Source: Hamman (1982) as summarized by Valdez and Ryel (1997).

4.4.6.2.1.3 Larvae

Newly hatched humpback chub larvae average 6.3–7.5 mm TL (Holden 1973; Suttkus and Clemmer 1977; Minckley 1979; Snyder 1981; Hamman 1982; Behnke and Benson 1983; Muth 1990), and 1-month-old fish are approximately 20 mm long (Hamman 1982). Swim-up occurs about 12 h after hatching at 19–22°C. Larvae increased 5–7 fold in total length during 56 d of culture at 12.8–25.5°C (Hamman 1982). Unlike Colorado pikeminnow and razorback sucker larvae, humpback chub larvae show no evidence of long-distance drift (Miller and Hubert 1990; Robinson et al. 1998). Upon emergence from spawning gravels, humpback chub larvae remain in the vicinity of bottom surfaces (Marsh 1985) near spawning areas (Chart and Lentsch 1999). It is hypothesized that they feed on small organisms on nearby substrates or at the surface in local low-velocity habitats. Movement away from spawning and hatching sites to downstream locations has been observed after large flash-flood events in the Little Colorado River, and density-dependent dispersal may also occur (Valdez and Ryel 1995). Larvae and juveniles under laboratory conditions have been observed schooling while feeding off the bottom until they were about 2 months of age (Hamman 1982).

4.4.6.2.2 Summer and Autumn

4.4.6.2.2.1 Adults

Adult movements and habitat use (nonspawning period).—Humpback chubs move substantially less than other Colorado River fishes and exhibit a strong fidelity for restricted reaches of river (Valdez and Clemmer 1982; Valdez and Ryel 1995, 1997). Studies on movement of humpback chubs demonstrated that the species has a strong affinity for discrete locations, although actual recorded movements vary somewhat depending on the methods used (i.e., capture-recapture versus radiotelemetry) and the population studied. Some of the earliest movement data for *Gila* in the Green River were reported by Valdez and Clemmer (1982), who summarized unpublished data by H. M. Tyus showing that one roundtail chub, one bonytail, and seven humpback chubs were recaptured at original capture sites in Desolation and Gray Canyons. Chart and Lentsch (2000) recorded no movement for nine chubs (242–397 mm TL) that they tagged and subsequently recaptured in Desolation and Gray Canyons. In Westwater Canyon, Chart and Lentsch (1999) PIT-tagged 837 humpback chubs and 1,070 roundtail chubs and subsequently recaptured 57 humpback and 71 roundtail chubs. Of the recaptures, 82.8% of the humpback chubs and 92% of the roundtail chubs showed no net movement; maximum movement observed was for a single humpback chub that moved 4.2 km upstream. Valdez and Clemmer (1982) reported that 8 radio-tagged humpback chubs in Black Rocks moved 0–3.7 km (mean, 0.8 km) and that 16 recaptured Carlin-tagged humpback chubs from Black Rocks and Westwater Canyon moved 0–23.0 km (mean, 1.6 km). Kaeding et al. (1990) reported a maximum movement of 1.4 km for 33 radio-tagged humpback chub adults in Black Rocks. The fishes' fidelity to specific main-stem localities (excluding spawning migrations) was striking in each of these studies. However, recent mark-recapture efforts to derive better population estimates in Westwater Canyon and Black Rocks have revealed some longer-ranging movements. Chart and Lentsch (1999) reported that in 1997, Colorado Division of Wildlife biologists recaptured two humpback chubs in Black Rocks (at RK 219.9) that were originally tagged in Westwater Canyon (at RK 198.6 and 194.4). Since then, several other incidences of humpback chub moving between these areas have been documented (C. W. McAda, U.S. Fish and Wildlife Service, personal communication).

In the Grand Canyon, 60 PIT-tagged fish captured in the main stem Colorado River, the Little Colorado River, and then again in the main stem, were all recaptured within 2.5 km of their previous main-stem locales: 54 (90%) were recaptured within 2 km, 31 (52%) within 0.5 km, and 10 (17%) within 0.1 km (Valdez and Ryel 1995). Overall movement (excluding spawning migrations) of 69 radio-tagged humpback chub adults in the Grand Canyon that were monitored throughout the year in the main-stem river averaged 1.49 km (range of 0–6.11 km; Valdez and Ryel 1995, 1997).

Humpback chubs in the Yampa River moved into deep pools during low flows in summer and early autumn, suggesting that these fish remain in nearby deep habitats during low-flow periods (Karp and Tyus 1990b). Similar observations were made for adult and juvenile humpback chubs in the Little Colorado River, with most adults remaining in the deepest pools (Gorman 1994). No seasonal changes in habitat use were noted in the main-stem Colorado River in the Grand Canyon, possibly because the lack of significant flow change between seasons allowed the continued use of large, recirculating eddies by adult fish (Valdez and Ryel 1995).

4.4.6.2.2.2 Juveniles

Growth and survival.—Growth and survival of postlarval humpback chubs are strongly influenced by water temperature. In the laboratory, Lupher and Clarkson (1994) observed a growth rate of 0.35 mm/d at 20°C, but only 0.08 mm/d at 10°C. Valdez and Ryel (1995) estimated a growth rate of 0.34 mm/d from back-calculations of scale growth in wild juveniles from the Little Colorado River, where average summer temperatures typically range from 18 to 24°C. They also calculated growth rates of juveniles in the main-stem Colorado River ranging from 0.12 to 0.13 mm/d; here, average summer temperatures generally range from 10 to 11°C. These growth rates were slightly higher than laboratory results and were attributed to the fishes' periodic occupation of warmer shoreline habitats. In the Green River, Chart and Lentsch (2000) reported faster growth of YOY chubs when average summer flows were lowest and main-channel temperatures were highest. Chart and Lentsch (1999) reported YOY growth rates for July and August in and upstream of Westwater Canyon that ranged from 0.15 mm/d in August 1995 to 0.83 mm/d in August 1994. They found that monthly growth rates and respective monthly degree-days warmer than 20°C were positively correlated (r^2 = 0.59; P = 0.02). Lowest growth and survival of young *Gila* in their study occurred in 1995, a year with a high, late runoff and cooler-than-normal water temperatures.

It appears that growth rates of humpback chubs vary considerably by population. Mark-recapture data for humpback chubs from Westwater Canyon (T. E. Chart, Utah Division of Wildlife Resources, personal communication) demonstrated mean growth rates of 1.08 mm/month for fish 200–250 mm TL and 1.35 mm/month for fish 250–300 mm TL. These growth rates are similar to those for juvenile humpback chubs from the Little Colorado River (1.33 and 1.08 mm/month; Valdez and Ryel 1995) but well below those for juvenile and adult humpback chubs from the main-stem Colorado River in the Grand Canyon (2.79 and 2.50 mm/month; Valdez and Ryel 1995).

Research in Desolation and Gray Canyons and Westwater Canyon has provided insights into several factors that appear be important to the survival and recruitment of humpback chubs. Important factors that influence recruitment of young chubs include warm, extended growing seasons that increase the size of young fish as winter approaches and the relative abundance of nonnative fishes, especially channel catfish. Sampling in Westwater Canyon has demonstrated that survival of juvenile chubs, as indicated by electrofishing captures, is high once fish reach 100 mm TL. Overwinter survival of YOY chubs also appears to be related to the size of fish as winter approaches, with larger fish exhibiting greater overwinter survival. In Westwater Canyon, overwinter survival of chubs was high in 1994 and was primarily attributed to the relatively large size of YOY fish as winter approaches (mean TL of 45 mm on 18 August 1994). Day et al. (2000) reported good overwinter survival of chubs in Desolation Canyon when fish were up to 45 mm TL as the winter approached in 1993. However, in 1994, chubs larger than 45 mm TL as winter approached did not exhibit high overwinter survival, implying other limiting factors, including nonnative fishes, were acting on them. Chart and Lentsch (2000) suggested that channel catfish, which are relatively more abundant in Desolation and Gray Canyons than in Westwater Canyon, may be partially responsible for the reduced abundance of chubs in the Green River. On the basis of research conducted on *Gila* in Desolation and Gray Canyons, Chart (2000) recommended base flows during dry years of 57 to 113 m^3/s to provide stable backwater and shoreline habitats for humpback chubs.

In summary, recruitment of humpback chubs depends on a number of physical and biological factors that are directly or indirectly influenced by flow regimes. Because of the extremely complex nature of the interactions, relationships linking flows to specific biological parameters are difficult to establish. However, empirical measurements of biological responses to flow regimes over a number of years provide useful information on the flow needs of humpback chubs. There is evidence of strong humpback chub recruitment in Desolation and Gray Canyons in the high water years (peak flows up to 1,250 m^3/s at Green River, Utah) prior to 1986 and in a subsequent series of moderate to high water years (peak flows from 650 to 830 m^3/s) in 1993, 1995, and 1996 (Chart and Lentsch 2000). Similarly, a combination of moderate to high water years on the Colorado River appeared to benefit the humpback chub population in Westwater Canyon (Chart and Lentsch 1999).

Habitat use by postlarval to juvenile humpback chubs.—In the postlarval stage (up to approximately 40 mm TL), humpback chubs occupy a variety of shoreline habitats characterized by adequate cover. Habitats utilized by these small fish include backwaters, small eddies, secondary channels, and embayments (Valdez et al. 1990). Day et al. (2000) examined backwater use by YOY

Gila in Desolation and Gray Canyons in a study that focused on backwater use and did not sample other low-velocity habitats. They found that chubs did not appear to select for a certain type (based on mechanism of formation) of backwater. The study, however, did report that young chubs consistently used backwaters that were larger and more turbid.

As young humpback chubs grow, they exhibit an ontogenic shift toward deeper and swifter offshore habitats. In Westwater Canyon during summer, fish smaller than 40 mm TL used low-velocity areas, including backwaters and shorelines. Later in summer and fall, as fish attained lengths of 40–50 mm TL, their habitat use shifted toward higher-velocity, flowing-water habitats (Chart and Lentsch 1999). Karp and Tyus (1990b) reported similar habitat use by larger humpback chubs, noting that fish 88–228 mm TL in the Yampa and Green Rivers used habitats consisting of rocky shoreline runs and small shoreline eddies. Average depths selected by larvae, YOY, juveniles, and adults in the upper basin were 0.4, 0.6, 0.7, and 3.1 m, respectively (Valdez et al. 1990), and average velocities were 0.03, 0.06, 0.18, and 0.18 m/s, respectively. Dominant substrates were silt and sand for YOY, and boulders, sand, and bedrock for juveniles and adults.

Valdez and Ryel (1995, 1997) also reported ontogenic shifts in habitat use by humpback chubs in the Grand Canyon. In the main-stem Colorado River, subadults (50–200 mm TL) primarily used shallow shoreline habitats; adults primarily used offshore habitats at greater depths. Minimum, average, and maximum velocities selected by YOY (21–74 mm TL) were 0.0, 0.06, and 0.30 m/s, respectively, all at depths less than 1 m. Minimum, average, and maximum velocities selected by juveniles (75–259 mm TL) were 0.0, 0.18, and 0.79 m/s, respectively, all at depths less than 1.5 m. In the Little Colorado River, Gorman (1994) found that juveniles or early stages less than 50 mm TL occupied near-benthic to mid-pelagic positions in shallow, nearshore areas that were less than 10 cm deep and had low-velocity flow, small substrate particle sizes, moderate cover, and vertical structure. Larger juveniles or fish 50–100 mm TL used similar habitats of moderate depth (less than 20 cm) that had small to large substrate particle size, moderate to high cover, and vertical structure. Juveniles (100–150 mm TL) used shoreline and offshore areas of moderate to deep water (less than 30 cm during the day; less than 20 cm at night) that had slow currents, small and large substrate particle size, moderate to high levels of cover, and vertical structure.

Habitat availability for young humpback chub during post-runoff.—In the Green River (Desolation and Gray Canyons), complex shorelines provide the necessary low-velocity habitats required by young humpback chubs. Orchard and Schmidt (2000) found that low flows (approximately 59–70 m^3/s) result in highly complex shoreline habitats with predominately bare sand and gravel substrates. Increasing flows submerged bare sand and gravel bars and reduced shoreline complexity (i.e., they reduced the number of different habitats available as a product of channel geomorphology). Chart (2000) recommended base flows of 57–113 m^3/s during dry years in Desolation and Gray Canyons on the basis of the persistence of warm, stable backwaters and other shoreline features utilized by humpback chubs. Day et al. (2000) found that the dominant backwater class in Desolation and Gray Canyons was shoreline eddy (backwaters formed as flows receded in recirculation zones). They found that the number of shoreline eddy backwaters was negatively correlated with flows during sampling periods but was not significantly correlated with peak-flow events.

4.4.7 Summary of Seasonal Flow-Habitat Relationships for Humpback Chub in the Green River System

This section focuses on the seasonality of humpback chub life history in the context of flow-habitat relationships in the Green River system. Table 4.10 at the end of this section summarizes flow and temperature needs by season and river reach. Information summarized here from preceding sections was used to make integrated flow and temperature recommendations to benefit endangered fishes in the Green River downstream of Flaming Gorge Dam (Chapter 5).

4.4.7.1 Spring

The humpback chub requires relatively warm temperatures for spawning, egg incubation, growth, and survival. Humpback chubs spawn in spring during a 4–5 week period, usually on the descending limb of the hydrograph at water temperatures greater than 17ºC. They spawn over a relatively wide range of flows and tend to spawn later in high water years with colder water temperatures and earlier during warmer low water years when temperatures are near optimum (approximately 20ºC). Optimum hatching of eggs and survival of larvae in the laboratory has been documented at water temperatures of 19–22ºC. Specific habitats used for spawning are believed to be midchannel cobble or gravel bars as well as lateral cobble bars and shoals associated with shoreline eddies. Although flows required to maintain spawning habitats are not known, flows of sufficient magnitude are needed to inundate and scour cobble bars of fine sediments to enhance egg survival. Adult humpback chubs use large recirculating eddies during most of the year, particularly in spring, for resting and feeding on food materials entrained by high flows in the eddy currents.

High spring flows that simulate the magnitude and timing of the natural hydrograph provide a number of benefits to humpback chubs in the Green River. Bankfull and overbank flows provide allochthonous energy input to the system in the form of terrestrial organic matter and insects that are utilized as food. High spring flows clean spawning substrates of fine sediments and provide physical cues for spawning. High flows also form large recirculating eddies used by adult fish. High spring flows (50% exceedance or greater) have been implicated in limiting the abundance and reproduction of some nonnative fish species under certain conditions (see section 4.1.2) and have been correlated with increased recruitment of humpback chubs (Chart and Lentsch 2000). Flows in Desolation and Gray Canyons that exceed 458 m^3/s maximize the amount of large recirculating eddies, habitats that are heavily utilized by adult and subadult humpback chubs during spring runoff. Chart (2000) recommended that during moderate to wet years, peak flows should reach approximately 708 m^3/s in Reach 3, and the full breadth of the spring-runoff period should last 60 d or more.

In Reach 1 and the upper portion of Reach 2, flow and temperature regimes are marginal to maintain viable humpback chub populations in most years. Management of flow and temperature releases from Flaming Gorge Dam to achieve temperatures greater than 17ºC during the declining limb of the spring hydrograph in Lodore Canyon and Whirlpool Canyon are recommended to enhance the potential for humpback chub spawning in Lodore Canyon (in lower Reach 1) and Whirlpool and Split Mountain Canyons (in upper Reach 2).

4.4.7.2 Summer and Autumn

During summer and autumn, base flows should be relatively stable and sufficiently warm (greater than or equal to 20ºC) to provide suitable nursery environments for humpback chub larvae and YOY. Young chubs utilize a variety of low-velocity habitats (e.g., shorelines, backwaters, and eddies) but seem to prefer areas with an abundant structure (e.g., talus, debris fans, and vegetation). Base flows of 70 m^3/s or less in Reach 3 result in complex shorelines in Desolation and Gray Canyons that should benefit early life stages of humpback chub. Chart (2000) recommended base flows during dry years between 57 and 113 m^3/s in Desolation and Gray Canyons for maintaining warm, stable shoreline habitats, including backwaters.

Increased release temperatures (up to 15ºC) at Flaming Gorge Dam in concert with low summer and autumn base flows may create suitable thermal conditions for humpback chubs in Lodore Canyon and in the upper sections of Reach 2 (Whirlpool and Split Mountain Canyons). Flow management and modification of temperature releases from Flaming Gorge Dam should target a temperature of about 20ºC during the summer base-flow period in Lodore Canyon and Whirlpool Canyon to provide favorable conditions for potential humpback chub reproduction and recruitment in those areas.

4.4.7.3 Winter

Little is known about the specific winter-flow requirements of humpback chub. To meet requirements of Colorado pikeminnow and razorback sucker, it is recommended that base flows in summer and autumn continue through winter. Relatively low and stable winter flows would provide stable, shoreline habitats in Whirlpool, Split Mountain, Desolation, and Gray Canyons and could increase overwinter survival of young fish. In Desolation and Gray Canyons, flows between 59 and 70 m^3/s result in highly complex shoreline habitats with large eddies preferred by humpback chub. Flows between 57 and 113 m^3/s provide stable shoreline habitats for humpback chub.

Table 4.10.—Summary of flow and temperature needs of humpback chub in the Green River system, Utah and Colorado.

Season	River Reach[a]		
	1	2	3
Spring	● Onset of releases from Flaming Gorge Dam closely coordinated with forecasts of spring runoff flows for the Yampa River (timed to supplement Yampa River peak and immediate post-peak flows) to provide flows compatible with requirements for downstream reaches ● Releases that decline in late spring or early summer in a pattern that simulates a natural hydrograph. Flow and temperature management that target water temperatures greater than 17°C during the declining limb of the spring runoff that could result in humpback chub spawning in Lodore Canyon. ● Occasional high flows (> 244 m^3/s) to maintain potential habitats in Lodore Canyon.	● Flow and temperature regimes that simulate pre-Flaming Gorge Dam conditions to provide spawning cues and suitable conditions for growth and gonadal maturation of fish in Whirlpool and Split Mountain Canyons. ● Temperature of releases from Flaming Gorge Dam should be managed to target temperatures greater than 17°C in Whirlpool Canyon during the declining limb of the spring runoff to increase the potential for humpback chub reproduction in Whirlpool and Split Mountain Canyons. ● Overbank flows (> 527 m^3/s) to reestablish river-floodplain connections for restoration of the ecosystem. ● High flows that scour and maintain large recirculating eddies as resting and feeding habitats for adults. ● Occasional high flows that reduce the abundance of nonnative fishes in low-velocity habitats.	● Flows that scour sediment and rework substrate in spawning areas in Desolation and Gray Canyons. ● Flows that maintain habitat complexity and help prevent channel narrowing ● Overbank flows (> 623 m^3/s) to reestablish river-floodplain connections for restoration of the ecosystem. ● Flows that provide natural temperature regimes for growth and gonadal maturation of fish in Desolation and Gray Canyons. ● Occasional high flows that reduce the abundance of nonnative fishes in low-velocity habitats. ● High flows that scour and maintain large recirculating eddies as resting and feeding habitats for adults. – Flows greater than 458 m^3/s provide large recirculating eddies in Desolation and Gray Canyons as habitat for adults during the spring runoff period. – Flows of approximately 708 m^3/s during moderate to wet years appear to benefit *Gila* reproduction in Desolation and Gray Canyons.

Table 4.10.—Continued.

Season	River Reach[a]		
	1	2	3
Summer/ Autumn	● Releases from Flaming Gorge Dam that simulate natural flow and temperature regimes, compatible with flow requirements for downstream reaches. – Base flow conditions in Reach 1 should be achieved as soon as possible after spring runoff to extend the warm summer growing season. Summer water temperatures of approximately 20ºC in the lower portions of the reach to provide potential habitat for humpback chubs.	● Flows that provide natural temperature regimes for egg hatching, larval survival, and growth in Whirlpool Canyon and Split Mountain Canyon. Flows and temperatures in the Green River should be managed to target water temperatures greater than 20ºC during the summer base-flow period.	● Flows that maintain recirculating eddies in Desolation and Gray Canyons as habitat for adults and large juveniles. ● Flows that provide natural temperature regime for egg hatching, larval survival, and growth in Desolation and Gray Canyons. ● Flows that provide relatively stable, complex shoreline habitat for young fish. – Base flows of less than 70 m^3/s provide complex shoreline habitats for humpback chubs in Desolation and Gray Canyons. – Base flows between approximately 57 and 113 m^3/s in Desolation and Gray Canyons provide warm relatively stable backwater and shoreline habitats.
Winter	● Releases from Flaming Gorge Dam that simulate natural flow and temperature regimes, compatible with flow requirements for downstream reaches.	● Relatively stable daily flows at levels similar to those in autumn to provide large recirculating eddies and stable shorelines in Whirlpool and Split Mountain Canyons.	● Relatively stable daily flows at levels similar to those in autumn to provide large eddies and stable shorelines in Desolation and Gray Canyons.

Table 4.10.—Continued.

Season	River Reach[a]		
	1	2	3
Winter (Cont.)			**–** Base flows less than 70 m^3/s provide complex shoreline habitats for humpback chubs in Desolation and Gray Canyons. **–** Base flows between approximately 57 and 113 m^3/s provide relatively stable backwater and shoreline habitats.

[a] River reaches: (1) Flaming Gorge Dam to Yampa River confluence, (2) Yampa River confluence to White River confluence, and (3) White River confluence to Colorado River confluence.

5 FLOW AND TEMPERATURE RECOMMENDATIONS

The Green River system in Utah and Colorado is one of the last remaining strongholds for endangered humpback chub, Colorado pikeminnow, and razorback sucker in the Colorado River basin, and it is considered vital to the recovery of these federally protected species. This chapter presents recommendations that are expected to provide the annual and seasonal patterns of flow and temperature in the Green River needed to improve habitats and enhance populations of the endangered fishes downstream of Flaming Gorge Dam. The recommendations are based on current understanding of the Green River system and interactions between physical and biological processes. They are drawn from the information on hydrology, geomorphology, and species biology reviewed in Chapters 3 and 4. As described in Chapter 2, a lines-of-evidence approach and professional judgment were used to develop these recommendations, since cause-and-effect experiments designed to determine the biological responses of these endangered fishes to flow and temperature could not be adequately performed in this large, complex river system.

5.1 SUMMARY OF SPECIES FLOW AND TEMPERATURE NEEDS

This section summarizes and integrates the information presented in Chapter 4 on the flow and temperature needs of the three endangered fishes in the Green River system. Flow and temperature recommendations for Reaches 1, 2, and 3 of the Green River (Section 5.2) target specific species and life stages (Table 5.1) and incorporate interannual variability to ensure that the varied needs of the endangered fishes are met. Recommendations for Reach 1 are limited to Lodore Canyon because suitable water temperatures and other habitat needs are unlikely to be met upstream of the canyon. Within this portion of the river, recommendations specifically target Colorado pikeminnow because adults are known to occur there now, and flow and temperature management could provide conditions suitable for pikeminnow spawning in Lodore Canyon. These recommendations may also benefit the few adult razorback suckers that now occur in Lodore Canyon and potentially allow for expansion of humpback chubs into this area. However, specific recommendations for those species in Reach 1 are not warranted at this time. Recommendations for Reaches 2 and 3 target all species and life stages and reflect the importance of these reaches for populations of the endangered fishes in the Green River. Chapter 4 has supporting details.

Colorado pikeminnow.—Life history and habitat requirements of Colorado pikeminnow in the Green River system (Section 4.2) are better understood than those of razorback sucker and humpback chub. Colorado pikeminnow are widespread in the system, occurring in both the main stem and tributaries. The Green River downstream of its confluence with the Yampa River supports the largest population of adults and nearly all larval and juvenile rearing areas; thus, this portion of the system is critical for sustaining Colorado pikeminnow populations. Reproduction of Colorado pikeminnow occurred in all years studied, and the current abundance of adults is comparatively high. However, the abundance of larval and age-0 stages is highly variable among years and is currently

Table 5.1.—Current known occurrence (K) or future potential occurrence with implementation of flow and temperature recommendations (P) of life stages of endangered fishes in three Green River reaches.[a]

Species and Life Stage	River Reaches[b]		
	1 (Lodore Canyon)[c]	2	3
Colorado pikeminnow			
Subadults/adults	K	K	K
Spawning	P		K
Larvae	P[d]	K	K
Juveniles		K	K
Razorback sucker			
Subadults/adults	K	K	K
Spawning		K	K[e]
Larvae		K	K
Juveniles		K	K
Humpback chub			
Subadults/adults	P	K	K
Spawning	P	P	K
Larvae	P	P	K
Juveniles	P	P	K

[a] Known occurrence is based on documented captures. Potential occurrence is based on known or likely historic presence of endangered fishes or their habitats.

[b] River reaches: (1) Flaming Gorge Dam to Yampa River confluence, (2) Yampa River confluence to White River confluence, and (3) White River confluence to Colorado River confluence.

[c] Potential occurrence of endangered fishes in Reach 1 is limited to Lodore Canyon because suitable water temperatures and other habitat needs are unlikely to be met upstream.

[d] Potential occurrence limited to drifting larvae.

[e] Strongly suspected on the basis of recent collections of larvae and early juveniles.

low compared to the abundance observed in the late 1980s. Recruitment has been low or nonexistent in some reaches and years.

Habitat requirements of Colorado pikeminnow vary by season and life stage. In spring, adults utilize warmer off-channel and floodplain habitats for feeding and resting. Declining flow, increasing water temperature, photoperiod, and perhaps other factors in early summer provide cues for reproduction. Declining flow in summer also removes fine sediments from spawning substrates, and increases in water temperature also aid gonadal maturation. Reproduction begins when water temperatures reach 16–22°C. After hatching and swim-up, larvae drift downstream and occupy channel-margin backwaters. The potential for cold shock to Colorado pikeminnow larvae drifting from the Yampa River and into the Green River in summer could be eliminated or reduced if warmer water was provided in Reach 1 (Flaming Gorge Dam to the Yampa River confluence). Warm water also promotes fast growth of Colorado pikeminnow, which reduces effects of size-dependent regulatory processes such as predation. This warmer water also may provide conditions suitable for spawning in Lodore Canyon of Reach 1 and would enhance growth of early life stages in nursery habitats (e.g., backwaters) throughout Reach 2 (Yampa River to the White River confluence). Low, relatively stable base flows create warm, food-rich backwaters that are thought to promote enhanced growth and survival of early life stages through autumn and winter. Similarly, low, relatively stable winter flows may enhance overwinter survival by reducing disruption of ice cover and habitat.

In-channel habitats used by Colorado pikeminnow are formed and maintained by spring peak flows that rework existing sediment deposits, scour vegetation from deposits, and create new habitats. The magnitudes of these flows were highly variable prior to flow regulation, and this variability appears to be important for maintaining high-quality habitats. In-channel habitats preferred by young Colorado pikeminnow are relatively deep (mean, 0.3 m) chute-channel backwaters. High peak flows maintain these habitats by periodically removing accumulated sediments and rebuilding the deposits that provide the structure for formation of backwaters after flows recede.

Razorback sucker.—Current levels of recruitment of young razorback suckers are not sufficient to sustain populations in the Green River system; wild stocks are composed primarily of older individuals that continue to decline in abundance (Section 4.3). Lack of adequate recruitment has been attributed to extremely low survival of larvae and juveniles. Reproduction by razorback suckers in the Green River was documented through captures of larvae each year during 1992–1996, but mortality of larvae was apparently high, possibly as a result of low growth rates and the effect of small body size on competition and the risk of predation. Only six juveniles have been collected from Green River backwaters since 1990, but 73 juveniles were collected from the Old Charlie Wash managed wetland in Reach 2 during 1995–1996.

Floodplain areas inundated and temporarily connected to the main channel by spring peak flows appear to be important habitats for all life stages of razorback sucker, and the seasonal timing of razorback sucker reproduction suggests an adaptation for utilizing these habitats. However, the frequency, magnitude, and duration of seasonal overbank flooding in the Green River have been substantially reduced since closure of Flaming Gorge Dam. Restoring access to these warm and productive habitats, which are most abundant in Reach 2 within the Ouray NWR area, would provide the growth and conditioning environments that appear crucial for recovery of self-sustaining razorback sucker populations. In addition, lower, more stable flows during winter may reduce flooding of low-velocity habitats and reduce the breakup of ice cover in overwintering areas and may enhance survival of adults.

Spring peak flows must be of sufficient magnitude to inundate floodplain habitats and timed to occur when razorback sucker larvae are available for transport into these flooded areas. Overbank flows of sufficient duration would provide quality nursery environments and may enhance the growth and survival of young fish. Because at least some young razorback suckers entrained in more permanent ponded (depression) sections of floodplains may survive through subsequent winters, spring inundation will need to be repeated at sufficiently frequent intervals to provide access back into the main channel.

Humpback chub.—Humpback chubs occur in the Green River in Whirlpool and Split Mountain Canyons in Reach 2, but they are most abundant in Desolation and Gray Canyons in Reach 3 (White River to the Colorado River confluence; Section 4.4). The habitat requirements of the humpback chub are incompletely understood. It is known that fish spawn on the descending limb of the spring hydrograph at temperatures greater than 17°C. Rather than migrate, adults congregate in near-shore eddies during spring and spawn locally. They are believed to be broadcast spawners over gravel and cobble substrates. Young humpback chubs typically use low-velocity shoreline habitats, including eddies and backwaters, that are more prevalent under base-flow conditions. After reaching approximately 40–50 mm TL, juveniles move into deeper and higher-velocity habitats in the main channel.

Increased recruitment of humpback chubs in Desolation and Gray Canyons was correlated with moderate to high water years from 1982 to 1986 and in 1993 and 1995. Long, warm growing seasons, which stimulate fish growth, and a low abundance of competing and predatory nonnative fishes also have been implicated as potential factors that increase the survival of young humpback chubs.

High spring flows increase the availability of the large eddy habitats utilized by adult fish. High spring flows also maintain the complex shoreline habitats that are used as nursery habitat by young fish during subsequent base flows. Low-velocity nursery habitats that are used by young fish are warmer and more productive at low base flows.

Integration of species flow and temperature needs.—As summarized above, life-history requirements of the endangered fishes vary among species and rely on different aspects of the hydrology and geomorphology of the Green River. Thus, it is not possible to make a single flow recommendation that would benefit all species in all years. Flows that restore dynamic hydrologic and geomorphic processes in the river are needed to enhance endangered fish populations. These dynamic processes are best provided by flows that vary among and within years. The magnitudes of effective flows are not the same for all portions of the Green River because tributary inputs and geomorphic differences along the river affect flow levels, seasonal flow and temperature patterns, channel hydraulics, bed characteristics, and sediment loads (Section 3.7).

Low-velocity backwater habitats are important for life stages of all three species. The availability and suitability of backwaters during the base-flow period are dependent on flow, but the relationship to flow will change from year to year as a function of the elevation of sediment deposits on which these habitats form (Section 3.6.2). Because these elevations are set by preceding high flows then eroded by subsequent flows, it is not possible or desirable to recommend a single flow that would optimize the areal extent of backwater habitats in all years. A specific recommendation for a given year should consider the magnitude of the spring peak and existing channel morphology.

Generally, base flows scaled to the magnitude of the spring peak and tied to annual hydrologic conditions (e.g., higher base flows in wetter years) should provide an appropriate quality and quantity of backwater habitats.

All three species benefit from dynamic sediment processes because these processes maintain preferred in-channel habitats and access to floodplains. Restoring the variability of peak flows is needed to prevent vegetation encroachment, channel narrowing, and vertical accretion of in-channel deposits and the river bank, which threaten to degrade the quality of endangered fish habitat.

Providing suitable spawning substrates within the channel for all species also requires maintenance of dynamic sediment processes. Cobble and gravel deposits used for spawning are relatively permanent features formed at very high flows (Section 3.6.3). Lower peak flows in subsequent years result in the deposition of fine sediments over the cobble and gravel deposits, but fine sediments are flushed as flows recede. Peak flows, whose timing coincides with the natural runoff cycle, are needed to ensure that suitable sites are available during the spawning period.

Inundation of floodplain habitats, although most important for the razorback sucker, would benefit all species by providing growth and conditioning environments and by restoring ecological processes dependent on periodic river-floodplain connections. Restoration of floodplain habitats could be achieved through a combination of increased peak flows, prolonged peak-flow duration, lower bank or levee heights, and constructed inlets (Section 3.6.5). The flow level necessary for floodplain inundation varies by reach, but our recommendations focus on Reach 2 within the Ouray NWR and the upper portion of Reach 3 between the White River and upper end of Desolation Canyon because the largest expanse of potentially flooded habitat occurs in these areas. Lower flow levels would be needed to initiate floodplain inundation in Reach 2 if existing levees were removed. Providing inundation of floodplain habitats in the lower portion of Reach 3 within Canyonlands National Park is problematic because of the vertical accretion (and natural levee formation) that has occurred.

5.2 RECOMMENDATIONS AND IMPLEMENTATION APPROACH

Our goal is to recommend annual and seasonal patterns of flow and temperature in the Green River that will enhance populations of the endangered fishes. To achieve this goal, specific objectives (Table 5.2) were identified on the basis of species needs summarized in Section 5.1. The objectives were formulated to meet all life-stage requirements of the endangered fishes by providing habitat conditions appropriate for spawning, hatching of eggs, transport of larvae to nursery areas, survival of larvae, and survival of juveniles to the reproductive adult stage. These recommendations span the full range of hydrologic conditions, cover all seasons of the year, and are intended to provide appropriate flows and temperatures in portions of the Green River downstream of Flaming Gorge Dam that are either occupied by endangered fishes or designated as critical habitat. When developing the recommendations, we identified flows and temperatures that, on the basis of review

Table 5.2.—Goal and objectives of flow and temperature recommendations for endangered fishes in the Green River downstream of Flaming Gorge Dam.

Goal:	Provide the seasonal and annual patterns of flow and temperature in the Green River that enhance populations of endangered fishes.
Objectives:	
1.	Provide appropriate conditions that allow gonadal maturation and environmental cues for spawning movements and reproduction.
2.	Form low-velocity flooded habitats for pre-spawning staging and post-spawning feeding and resting areas.
3.	Inundate floodplains and other off-channel habitats at the appropriate time and for an adequate duration to provide warm, food-rich environments for fish growth and conditioning and to provide river-floodplain connections for the restoration of natural ecosystem processes.
4.	Restore and maintain the channel complexity and dynamics needed for formation and maintenance of high-quality spawning, nursery, and adult habitats.
5.	Provide base flows that promote favorable conditions in low-velocity habitats during summer, autumn, and winter.
6.	Minimize differences in water temperature between the Green River and Yampa River in Echo Park to prevent cold shock and possible mortality to larval Colorado pikeminnow transported from the Yampa River into the Green during summer.

and synthesis of existing information and professional judgment, would benefit the endangered fishes given the existing hydrology and geomorphology of the Green River system. Our recommendations are based on the following information or assumptions.

- Populations of the endangered fishes and habitats required by all life stages are concentrated in Reaches 2 and 3 of the Green River.
- Habitat for endangered fishes in Reach 1 is limited to Lodore Canyon because of cold summer water temperatures upstream.
- Providing suitable habitat conditions through flow and temperature management at Flaming Gorge Dam will enhance endangered fish populations in the Green River.
- The current hydrology of the upper Green River basin, including inflows to Flaming Gorge Reservoir and available release volumes from Flaming Gorge Dam, will remain largely unaltered.
- Changes in flow, temperature, and sediment regimes in Green River tributaries (particularly the Yampa and White Rivers) will be consistent with existing or known pending biological opinions.

A fundamental aspect of our recommendations for the endangered fishes is to provide increased interannual variability in peak and base flows. This variability has been identified as critical to supporting in-channel and floodplain geomorphic processes that maintain the ecosystem dynamics to which these species are adapted. It is important to note that not all objectives for each species can or need to be met within each year. Different species occupy different ecological niches, and distinct life stages benefit from different specific hydrologic conditions. For all species, short-term adverse effects of high or low flows are thought to be offset by longer-term benefits. The recommended flow patterns, ranges, and frequencies approximate unregulated flow conditions more closely than the 1992 Biological Opinion and are intended to enhance the biological and physical conditions for each of the endangered fishes. To achieve the objectives of our flow recommendations, the magnitude, duration, and timing of releases from Flaming Gorge Dam should be tied to the anticipated hydrologic condition in a given year. This approach will tend to mimic the natural hydrology of the Green River basin and provide recommended levels of within-year and between-year variability.

Forecasted runoff volume should be used to determine the magnitude, duration, and timing of releases from Flaming Gorge Dam to enhance downstream habitat conditions. When above-average runoff conditions are forecasted, bypass tubes or the spillway at Flaming Gorge Dam should be used to enhance peak spring flows in downstream reaches. During average or drier years, releases in spring should be at maximum power-plant levels or greater to achieve specific target peak flows identified for that year in downstream reaches. Similar to peak flows, base flows during summer–winter should be tied to annual hydrologic conditions and should be higher in wetter years than in drier years.

The magnitude and duration of peak flows in Reaches 2 and 3 can be maximized by tying the peak release from Flaming Gorge Dam with spring peak and immediate post-peak flows of the Yampa River. Natural runoff cycles for the Green and Yampa Rivers are usually offset somewhat from each other because of climatic differences between the drainage basins. However, timing dam peak releases to coincide with the Yampa River peak and immediate post-peak period would increase the effectiveness of peak flows in restoring in-channel processes and inundating floodplain habitats and extend the duration of peak flows in Reaches 2 and 3.

Five hydrologic-condition categories are used in our recommendations to encompass the range of annual flows for the Green River. These five categories reflect the probability of occurrence of a given annual spring-runoff volume as determined from the historic record of inflow-runoff volumes to Flaming Gorge Dam. Hydrologic conditions in any given year can be placed in one of the following categories[6]:

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[6]Hydrologic conditions in this report are presented in terms of percent exceedance. Here, percent exceedance refers to percent of years in the historic record that had equal or greater flow volumes during the runoff period.

- ***Wet (0–10% exceedance).***—A year during which the forecasted runoff volume is larger than almost all of the historic runoff volumes. This hydrologic condition has a 10% probability of occurrence.

- ***Moderately wet (10–30% exceedance).***—A year during which the forecasted runoff volume is larger than most of the historic runoff volumes. This hydrologic condition has a 20% probability of occurrence.

- ***Average (30–70% exceedance).***—A year during which the forecasted runoff volume is larger than about half of the historic runoff volumes. This hydrologic condition has a 40% probability of occurrence.

- ***Moderately dry (70–90% exceedance).***—A year during which the forecasted runoff volume is less than most of the historic runoff volumes. This hydrologic condition has a 20% probability of occurrence.

- ***Dry (90–100% exceedance).***—A year during which the forecasted runoff volume is less than almost all of the historic runoff volumes. This hydrologic condition has a 10% probability of occurrence.

These exceedance intervals were chosen to provide guidance for setting peak- and base-flow targets under different hydrologic conditions to achieve the desired hydrologic variability. In reality, annual runoff volume is a continuous variable, and any categorization scheme is somewhat arbitrary. Release patterns in any given year should reflect where the hydrologic condition in that year falls within the wet to dry continuum.

Our recommendations include target flows and temperatures specific to each reach of the Green River downstream of Flaming Gorge Dam because habitats of the endangered fishes, hydrology, and geomorphology vary among the reaches. Flow and temperature recommendations and their anticipated effects on the endangered fishes and their habitats in each reach are presented in Sections 5.2.1, 5.2.2, and 5.2.3. However, because it is not feasible to cover every contingency in our recommendations, use of real-time and other available year-specific data (Table 5.3) should be factored into annual implementation of the recommendations. Yearly patterns of releases from Flaming Gorge Dam to meet the recommended flows and temperatures for each hydrologic condition should be adjusted on the basis of information about hydrology, the status of endangered fish life stages and populations, and habitat conditions. Reclamation, Western, and the Service should convene a technical working group of biologists and hydrologists to help refine release plans for each year and provide advice on modifying releases during changing hydrologic conditions.

Such a process was followed in 1999, when real-time and other year-specific data were used to pattern releases from Flaming Gorge Dam to benefit downstream endangered fish populations. Forecasted and actual spring runoff volumes in the upper Green River basin were used to forecast the expected hydrologic condition, which was identified as moderately wet. Once the hydrologic

Table 5.3.—Examples of real-time and other year-specific information to be considered in determining annual patterns of releases from Flaming Gorge Dam for implementation of flow and temperature recommendations to benefit endangered fishes in downstream reaches of the Green River.

Onset of Spring Peak Flow	Magnitude of Spring Peak Flow	Duration of Spring Peak Flow	Onset of Summer–Winter Base Flow	Magnitude of Summer–Winter Base Flow
• Forecasted and actual inflow to Flaming Gorge Reservoir • Water surface elevation of Flaming Gorge Reservoir • Forecasted and actual flows in the Yampa River • Presence of adult razorback sucker congregations on spawning bars • Initial appearance of larval suckers in established reference sites in Reach 2 (e.g., Cliff Creek) • Existing habitat conditions (e.g., condition of razorback sucker spawning sites in Reach 2)	• Forecasted and actual inflow to Flaming Gorge Reservoir • Forecasted and actual flow in the Yampa River and other large tributaries • Desired areal extent of overbank flooding in Reaches 2 and 3 • Flow conditions and extent of overbank flooding in Reaches 2 and 3 in previous year • Existing habitat conditions • Status of endangered fish populations	• Forecasted and actual inflow to Flaming Gorge Reservoir • Forecasted and actual flow in the Yampa River and other large tributaries • Desired duration of overbank flooding in Reaches 2 and 3 • Desired base-flow magnitude • Presence of razorback sucker larvae in the Green River • Existing habitat conditions • Status of endangered fish populations	• Forecasted and actual inflow to Flaming Gorge Reservoir • Forecasted and actual flow in the Yampa River • Initial appearance of drifting Colorado pikeminnow larvae in the Yampa River • Status of endangered fish populations • Temperature of water released from the dam • Temperature differences between the Green and Yampa Rivers at their confluence	• Forecasted and actual inflow to Flaming Gorge Reservoir • Forecasted and actual flow in the Yampa River • Elevation of sand bars in nursery areas • Status of endangered fish populations • Temperature of water released from the dam • Temperature differences between the Green and Yampa Rivers at their confluence

condition was determined, frequent interagency conference calls were made to update information on actual and forecasted hydrology and to integrate real-time biological and physical data in order to set peak and base flows. Information on the presence of adult razorback sucker congregations on spawning bars, the presence of bed-load sediment at razorback sucker spawning sites, the initial appearance of larval suckers, the presence of razorback sucker larvae in established reference sites, and the extent of overbank flooding are examples of the types of information that were used to help determine the onset, magnitude, and duration of spring peak flows. The onset and magnitude of summer–winter base flows were determined in part by using data on the initial appearance of drifting Colorado pikeminnow larvae in the Yampa River and data on the temperature of water being released from Flaming Gorge Dam.

Just as real-time data and other information should be used in determining the specific magnitude, duration, and timing of flows in any given year, the results of research and monitoring should be used to refine the flow and temperature recommendations (Section 5.6). Adaptive management is one approach that could be useful in modifying or adjusting recommendations in the future. A holistic system perspective on managing the water in the Green River basin is vitally important to successfully implement the recommendations. Tributaries provide habitat for endangered fishes and play an important role in maintaining the large-river characteristics of the main-stem Green River. These characteristics are required by the endangered fishes and other native fishes in the system.

5.2.1 Recommendations for Reach 1 — Flaming Gorge Dam to the Yampa River Confluence

Recommended flows for Reach 1 (Table 5.4) are those measured at the USGS gage near Greendale, Utah, and are, for the most part, release patterns from Flaming Gorge Dam needed to achieve the target peak and base flows identified for habitats of the endangered fishes in Reaches 2 and 3. However, flows in wetter years should be high enough for channel maintenance in Lodore Canyon to maintain habitats occupied by adult Colorado pikeminnow.

To achieve proper coordination with downstream flow needs in Reaches 2 and 3, it is important that the onset of peak releases from Flaming Gorge Dam is timed to coincide with peak and immediate post-peak spring flows in the Yampa River. It is also important that the largest possible volume of water consistent with reservoir operations be released during the spring to meet base-flow recommendations during the remainder of the year. Recommended base flows, achieved by the summer target dates, should be maintained until the initiation of the spring peak in the following year. Base flows in Reach 1 should be managed to ensure that within-year and within-day variability targets for Reach 2 are met.

Temperature levels and patterns that more closely approximate pre-dam conditions of the Green River would benefit endangered fishes in lower Reach 1 and upper Reach 2. We recommend that operations target water temperatures of 18–20^{o}C or greater in Lodore Canyon for a duration of 2–5 weeks beginning when base flow is achieved. Release temperatures and flow patterns should

Table 5.4.—Flow and temperature recommendations by hydrologic condition for Reach 1 (Flaming Gorge Dam to Yampa River) to benefit endangered fishes in the Green River downstream of Flaming Gorge Dam.[a]

	Hydrologic Condition[b]				
	Wet (0 to 10% Exceedance)	**Moderately Wet (10 to 30% Exceedance)**	**Average (30 to 70% Exceedance)**	**Moderately Dry (70 to 90% Exceedance)**	**Dry (90 to 100% Exceedance)**
SPRING PEAK FLOW					
General recommendation	Peak flows in Reach 1 should be of the magnitude, timing, and duration to achieve recommended peak flows in Reaches 2 and 3. In wetter years, peak flows should be of sufficient magnitude to restore and rebuild habitats currently occupied by adult Colorado pikeminnow in Lodore Canyon. No upper limits are placed on recommended peak-flow releases in any hydrologic condition. See Table 5.3 for examples of real-time and other year-specific information to be considered in determining characteristics of spring peak flows.				
Peak-flow magnitude	$\geq$ 244 m^3/s (8,600 cfs)	$\geq$ 130 m^3/s (4,600 cfs)			
Peak-flow duration	Duration of peak releases from the dam should be based on those needed to achieve recommended duration of bankfull and overbank flows in Reaches 2 and 3.				
Peak-flow timing	Peak releases should be timed to coincide with peak and immediate post-peak spring flows in the Yampa River.				
Anticipated effects[c]	Most effects will occur in Reaches 2 and 3 (see Tables 5.5 and 5.6). Significant channel maintenance (i.e., rework and rebuild in-channel sediment deposits, increase habitat complexity, and prevent or reverse channel narrowing) in Lodore Canyon in wet years or in other years when peak releases are greater than 244 m^3/s (8,600 cfs); channel maintenance will improve habitat conditions for endangered fishes and could favor potential spawning of Colorado pikeminnow in this portion of the river [Sections 3.6.2, 3.6.3, 3.6.4, 4.2.5.4; Objective 4].				
SUMMER THROUGH WINTER BASE FLOW					
General recommendation	The mean flow for the summer–winter period should be established each year on the basis of anticipated hydrologic conditions, but adjustments can be made if hydrologic conditions change. Releases from the dam should gradually decline from peak flow to base flow, with the base flow reached by early to middle summer (depending on hydrologic conditions) and maintained through February. See Table 5.3 for examples of real-time and other year-specific information to be considered in determining characteristics of summer through winter base flows.				
Mean base-flow magnitude[d]	50 to 76 m^3/s (1,800 to 2,700 cfs)	42 to 72 m^3/s (1,500 to 2,600 cfs)	23 to 62 m^3/s (800 to 2,200 cfs)	23 to 37 m^3/s (800 to 1,300 cfs)	23 to 28 m^3/s (800 to 1,000 cfs)

Table 5.4.—Continued.

	Hydrologic Condition[b]				
	Wet (0 to10% Exceedance)	**Moderately Wet (10 to 30% Exceedance)**	**Average (30 to 70% Exceedance)**	**Moderately Dry (70 to 90% Exceedance)**	**Dry (90 to 100% Exceedance)**
SUMMER THROUGH WINTER BASE FLOW (Cont.)					
Rate of decline from peak flow to base flow[e]	Approximately 28 m^3/s (1,000 cfs) per day	Approximately 28 m^3/s (1,000 cfs) per day	Approximately 14 m^3/s (500 cfs) per day	Approximately 10 m^3/s (350 cfs) per day	Approximately 10 m^3/s (350 cfs) per day
Base-flow period	About 15 August to 1 March	About 1 August to 1 March	About 15 July to 1 March	About 1 July to 1 March	About 15 June to 1 March
Base-flow variation	No specific recommendations are made for base-flow variation in Reach 1, but variation around the annual mean base flow should be restricted to achieve recommended levels of variation in Reach 2 (see Table 5.5).				
Water temperature	Water temperatures of 18ºC or greater for 2 to 5 weeks in the beginning of the base-flow period should be targeted in upper Lodore Canyon by managing flows and releasing water up to 15ºC. It may not be feasible to achieve these target water temperatures in wetter years.				
Anticipated effects[c]	Most targeted effects are for Reaches 2 and 3 (see Tables 5.5 and 5.6). Target water temperatures in Lodore Canyon are expected to be achieved in 7 of 10 years (average and drier years) and could result in Colorado pikeminnow spawning in this portion of the river [Section 3.5.1.1, 4.2.5.2.2, 5.2.1; Objective 1]; more favorable water temperatures also could result in expansion of humpback chubs into this portion of the river [Section 4.4.7.1; Objective 5].				

[a] Reach 1 is located between Flaming Gorge Dam (RK 659.8) and the Yampa River confluence (RK 555.1). This is the reach that is most affected by the presence and operation of Flaming Gorge Dam; except for minor flow contributions from tributary streams, flows in the Green River within this reach are completely regulated by the dam. Endangered fishes were present in this reach pre-dam; some adult Colorado pikeminnow and one adult razorback sucker have been collected recently. Recommended flows are those measured at the USGS gage near Greendale, Utah.

[b] See text for descriptions of the hydrologic conditions.

[c] Numbers in brackets [ ] refer to sections in this or previous chapters that contain information supporting the anticipated effects, and they also refer to objectives achieved by the flow recommendation (see Table 5.2 for a list of recommendation objectives).

[d] Ranges of base flows for each hydrologic condition were determined to be those needed to achieve target base-flow values in Reach 2 given the range of Yampa River base flows.

[e] Rate of decline from peak flow to base flow approximates the natural rate of decline in each hydrologic condition.

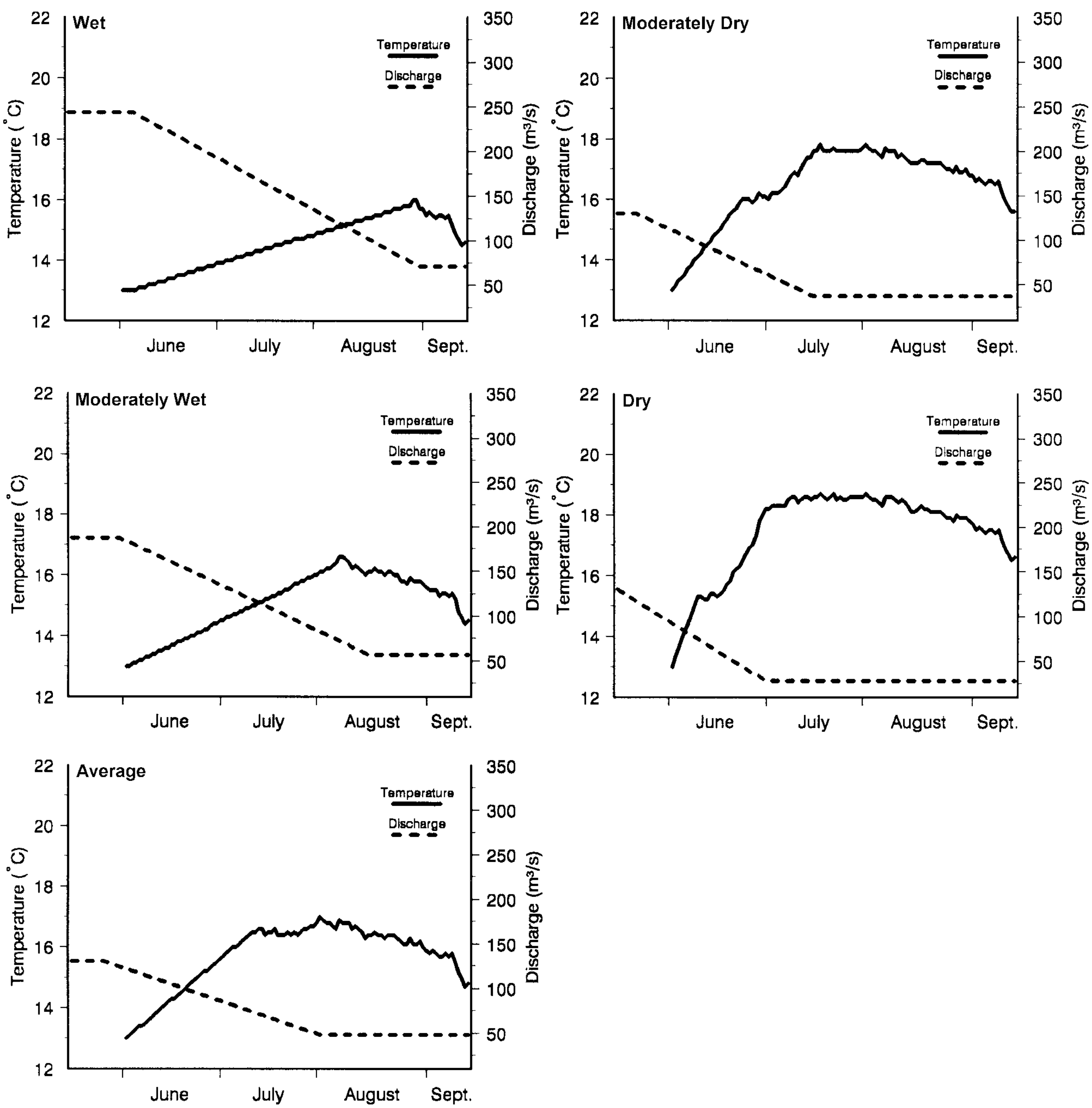
be managed to achieve these target temperature conditions. Simulations from an empirical regression model show that the target temperature conditions (level and duration) should be achieved under dry and moderately dry hydrologic conditions when 13ºC water is released from Flaming Gorge Dam (Section 3.5.1.1; Figure 5.1). During average, moderately wet, and wet hydrologic conditions, the temperature of water released from Flaming Gorge Dam may need to be increased up to 15ºC. Simulations suggest that target conditions should be achieved during average and perhaps moderately wet hydrologic conditions when there is such an increase in the release temperature. It is unlikely that target water temperature conditions will be achieved in some moderately wet and all wet hydrologic conditions because water does not have sufficient time to warm as it travels downstream. Warmer water would provide cues for adults migrating to spawning areas, aid gonadal maturation, enhance the likelihood of reproduction by Colorado pikeminnow in Lodore Canyon, and enhance growth of early life stages of fishes in nursery habitat including those in Echo, Island, and Rainbow Parks (all in Reach 2). Improving conditions in Lodore Canyon also could result in expansion of endangered fish populations into lower Reach 1 and upper Reach 2.

5.2.2 Recommendations for Reach 2 — Yampa River Confluence to the White River Confluence

Recommended flows for this reach (Table 5.5) are those measured at the USGS gage near Jensen, Utah. Anticipated effects of the recommendations will vary among years depending on hydrologic conditions. Recommended peak flows, especially in wet and moderately wet years, would inundate substantial floodplain areas near Ouray for durations adequate to provide nursery habitat for larval razorback suckers. Peak flows also should prevent or reverse channel narrowing, which would benefit Colorado pikeminnow and humpback chubs. Recommended low base flows in summer should produce suitable conditions in backwaters for growth of Colorado pikeminnow larvae.

Some variation in flow during the base-flow period was typical of the pre-dam Green River (Section 3.4.3) and occurred on several different time scales. Time scales included the variation that would occur in flow within a day, between consecutive days, and among mean daily flows during the entire base-flow period. Our recommendations for the base-flow period consider variation in flow at these three time scales (Figure 5.2).

Currently, base flows in Reach 2, particularly during late autumn, winter, and early spring, are subject only to natural variation in tributary flows because the natural variation in flow of the upper Green River has been eliminated by Flaming Gorge Dam operations. Prior to construction of Flaming Gorge Dam, the median annual CV of mean daily flows at Jensen over the August–February period was 48%. Operations have reduced this variation by about one-half (median annual CV of 25%). The summer–autumn period (August through November) was more variable (median annual CV of 41%) than winter (December through February; median annual CV of 28%). Median differences between consecutive days were about 3% before construction of the dam. We recommend that within-year and between-day variation in mean daily flows during the base-flow



Model predictions at flows greater than 85m³/s are unreliable; the straight-line portion of each temperature profile was produced by connecting the highest temperature predictions at flows greater than 85 m³/s with hypothetical minimum flows. Air temperature was an independent model variable and was the mean daily temperature for the period of record at Browns Park.

Figure 5.1.—Summer water temperatures for five hydrologic conditions in lower Browns Park of the Green River predicted by an empirical regression model. Source: Bestgen and Crist (2000)

Table 5.5.—Flow and temperature recommendations by hydrologic condition for Reach 2 (Yampa River to White River) to benefit endangered fishes in the Green River downstream of Flaming Gorge Dam.[a]

	Hydrologic Condition[b]				
	Wet (0 to 10% Exceedance)	**Moderately Wet (10 to 30% Exceedance)**	**Average (30 to 70% Exceedance)**	**Moderately Dry (70 to 90% Exceedance)**	**Dry (90 to 100% Exceedance)**
SPRING PEAK FLOW					
General recommendation	Peak flows in Reach 2 should be of the magnitude, timing, and duration to provide floodplain inundation in the Ouray portion of the river for at least 2 weeks in 4 of 10 years and at least bankfull flows in 1 of 2 years. In all years, peak flows should be of sufficient magnitude and duration to provide at least some in-channel habitat maintenance throughout the reach. No upper limits are placed on recommended peak flows in any hydrologic condition. The duration of peak flows less than 527 m^3/s (18,600 cfs) should be limited, because neither floodplain nor backwater habitats are available at these flows. See Table 5.3 for examples of real-time and other year-specific information to be considered in determining characteristics of spring peak flows.				
Peak-flow magnitude	$\geq$ 748 m^3/s (26,400 cfs)	$\geq$ 575 m^3/s (20,300 cfs)	$\geq$ 527 m^3/s (18,600 cfs) in 1 of 2 average years; $\geq$ 235 m^3/s (8,300 cfs) in other average years	$\geq$ 235 m^3/s (8,300 cfs)	
Peak-flow duration	Flows greater than 643 m^3/s (22,700 cfs) should be maintained for 2 weeks or more, and flows greater than 527 m^3/s (18,600 cfs) for 4 weeks or more.	Flows greater than 527 m^3/s (18,600 cfs) should be maintained for 2 weeks or more.	Flows greater than 527 m^3/s (18,600 cfs) should be maintained for at least 2 weeks in at least 1 of 4 average years.	Flows greater than 235 m^3/s (8,300 cfs) should be maintained for at least 1 week.	Flows greater than 235 m^3/s (8,300 cfs) should be maintained for 2 days or more except in extremely dry years ($\geq$ 98% exceedance).
Peak-flow timing	Peak flows should coincide with peak and immediate post-peak spring flows in the Yampa River.				

Table 5.5.—Continued.

	Hydrologic Condition[b]				
	Wet (0 to 10% Exceedance)	**Moderately Wet (10 to 30% Exceedance)**	**Average (30 to 70% Exceedance)**	**Moderately Dry (70 to 90% Exceedance)**	**Dry (90 to 100% Exceedance)**
SPRING PEAK FLOW (Cont.)					
Anticipated effects[c]	Significant inundation of floodplain habitat and off-channel habitats (e.g., tributary mouths and side channels) to establish river-floodplain connections and provide warm, food-rich environments for growth and conditioning of razorback suckers (especially young) and Colorado pikeminnow [Sections 3.6.2, 3.6.5, 4.2.5.2.1, 4.3.5.2.1.1, 4.3.5.2.1.3, and 4.4.6.2.1; Objectives 2 and 3].		Significant inundation of floodplain habitat and off-channel habitat in at least 1 of 4 average years; some flooding of off-channel habitats in all years [Sections 3.6.2 and 3.6.5; Objectives 2 and 3].	No floodplain inundation, but some flooding of off-channel habitats [Section 3.6.2; Objectives 2 and 3]. May benefit recruitment of Colorado pikeminnow in some years [Section 4.2.5.3; Objective 4].	
	Significant channel maintenance to rework and rebuild in-channel sediment deposits (including spawning substrates), increase habitat complexity, form in-channel sand bars, and prevent or reverse channel narrowing [Sections 3.6.2 and 3.6.4; Objective 4].		Significant channel maintenance in at least 1 of 2 average years [Sections 3.6.2 and 3.6.4; Objective 4].	Some channel maintenance in all years because flows exceed the incipient-motion threshold [Sections 3.6.2 and 3.6.4; Objective 4].	
	Provide conditions for gonadal maturation and cues for spawning migrations and reproduction by the endangered fishes [Sections 4.2.5.2.1, 4.3.5.2.1.1, and 4.4.6.2.1; Objective 1].				
SUMMER THROUGH WINTER BASE FLOW					
General recommendation	The mean flow for the summer–winter period should be established each year on the basis of anticipated hydrologic conditions, but adjustments can be made if hydrologic conditions change. Flow should gradually decline from peak flow to base flow, with the base flow reached by early to middle summer (depending on hydrologic conditions) and maintained through February. See Table 5.3 for examples of real-time and other year-specific information to be considered in determining characteristics of summer through winter base flow.				

Table 5.5.—Continued.

	Hydrologic Condition[b]				
	Wet (0 to 10% Exceedance)	**Moderately Wet (10 to 30% Exceedance)**	**Average (30 to 70% Exceedance)**	**Moderately Dry (70 to 90% Exceedance)**	**Dry (90 to 100% Exceedance)**
SUMMER THROUGH WINTER BASE FLOW (Cont.)					
Mean base-flow magnitude[d]	79 to 85 m^3/s (2,800 to 3,000 cfs)	67 to 79 m^3/s (2,400 to 2,800 cfs)	43 to 67 m^3/s (1,500 to 2,400 cfs)	31 to 43 m^3/s (1,100 to 1,500 cfs)	26 to 31 m^3/s (900 to 1,100)
Rate of decline from peak flow to base flow	Rate of decline will depend on rates of decline in Yampa River flows and recommended rates of decline for dam releases (see Table 5.4).				
Base-flow period	About 15 August to 1 March	About 1 August to 1 March	About 15 July to 1 March	About 1 July to 1 March	About 15 June to 1 March
Base-flow variation	Variation in flow around the established mean base flow should be consistent with the variability that occurred in pre-dam flows. Mean daily flows should be kept within ± 40% of the annual mean base flow in summer–autumn (August through November) and within ± 25% of the annual mean base flow in winter (December through February); however, dam operations should not be adjusted to compensate for short-term increases in tributary inflow resulting from weather events that would exceed these thresholds. Differences due to reservoir operations in mean daily flows between consecutive days should not exceed 3%. Flow variation resulting from hydropower generation at Flaming Gorge Dam should be limited to produce no more than a 0.1-m stage change within a day at the USGS gage near Jensen, Utah.				
Water temperature	Green River should be no more than about 5ºC colder than the Yampa River at their confluence in Echo Park during the summer base-flow period.				
Anticipated effects[c]	Base flows in summer and autumn scaled to the hydrologic condition favor the formation of backwaters and other low-velocity shoreline nursery habitats [Section 3.6.2; Objective 5].				
	Lower water temperatures at higher base flows in the wettest years may reduce growth and survival of young endangered fish [Sections 4.2.5.2.2, 4.2.5.3, 4.3.5.2.2.1, 4.4.6.2.2.2, and 5.2.2].		Higher water temperatures at lower base flows will enhance growth and survival of young endangered fish, particularly Colorado pikeminnow [Sections 4.2.5.2.2, 4.2.5.3, 4.2.5.4, and 4.4.6.2.2.2; Objective 5].		

Table 5.5.—Continued.

	HYDROLOGIC CONDITION[b]				
	Wet (0 to 10% Exceedance)	**Moderately Wet (10 to 30% Exceedance)**	**Average (30 to 70% Exceedance)**	**Moderately Dry (70 to 90% Exceedance)**	**Dry (90 to 100% Exceedance)**
SUMMER THROUGH WINTER BASE FLOW (Cont.)					
Anticipated effects*[c] *(Cont.)	Maintenance of the mean base flow within recommended levels of seasonal and within-day flow variability throughout summer, autumn, and winter will promote favorable conditions for all life stages of endangered fishes that use low-velocity habitats [Sections 3.6.2, 4.2.5.2.3, 4.2.5.4, 4.3.5.2.2, 4.3.5.2.3, and 4.4.6.2.2.2; Objective 5].				
	Gradually declining flows after the spring peak will provide reproductive cues to Colorado pikeminnow and humpback chub adults [Sections 4.2.5.1, 4.2.5.2.2, and 4.4.6.2.1; Objective 1].				
	Limiting differences in water temperature between the Green and Yampa rivers at their confluence in Echo Park will prevent cold shock to Colorado pikeminnow larvae drifting out of the Yampa River and into the Green River [Sections 3.5.1.1, 4.2.5.2.2, and 5.2.2; Objective 6]. Warmer temperatures also will promote better growth of endangered fishes in the upper portion of Reach 2 [4.2.5.2.2, 4.4.6.2.2.2; Objective 5].				

[a] Reach 2 is located between the Yampa River confluence (RK 555.1) and the White River confluence (RK 396.2). This reach exhibits more natural flow, temperature, and sediment regimes than Reach 1 because of inputs from the largely unregulated Yampa River. This reach serves as a dispersal corridor for Colorado pikeminnow and razorback sucker larvae produced in the lower Yampa River and provides nursery habitats for young Colorado pikeminnow and razorback suckers. This reach supports the largest extant reproducing riverine population of razorback suckers and contains the largest expanse of floodplain habitat in the upper Colorado River basin. Recommended flows are those measured at the USGS gage near Jensen, Utah.

[b] See text for descriptions of the hydrologic conditions.

[c] Numbers in brackets [ ] refer to sections in this or previous chapters that contain information supporting the anticipated effects, and they also refer to objectives achieved by the recommendation (see Table 5.2 for a list of recommendation objectives).

[d] The range of base-flow magnitudes for each hydrologic condition was determined by apportioning the total range of base flows (26 to 85 m^3/s; 900 to 3,000 cfs) into increments matching the width of each hydrologic-condition exceedance interval.

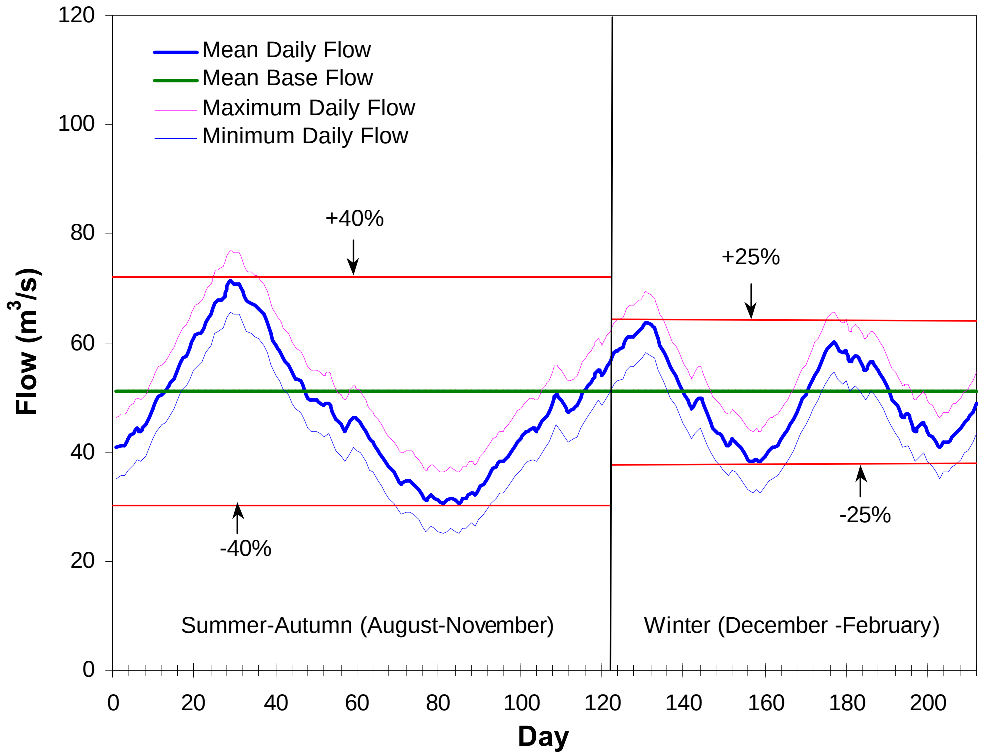


Figure 5.2.—Representation of recommendations for flow variability during the summer through winter base flow period in Reach 2. (In summer and autumn, mean daily flow should be within 40% of the mean annual base flow; in winter, mean daily flow should be within 25% of the mean annual base flow. The rate of change in mean daily flow should be 3% or less between consecutive days. Fluctuation between maximum and minimum daily flows should produce no more than a 0.1-m change in stage at the USGS stream gage near Jensen, Utah.)

period be consistent with pre-dam variability. However, we do not recommend that operations be adjusted to compensate for short-term increases in tributary inflow resulting from weather events that would result in flows outside of this range of variability or that would result in more rapid changes between days. On the basis of the stage-flow relationship near Jensen (Section 3.4.5), the maximum stage change that could occur with this level of flow variability over the summer through autumn period would be about 0.4 m. Flow variability in the winter (December through February) would produce a maximum stage change of about 0.2 m.

We recommend that the within-day variability in flows that result from hydropower operations be restricted to produce no more than a 0.1-m change in stage at the Jensen gage. This recommendation is based on the fact that the average depth of backwaters occupied by Colorado pikeminnow larvae in Reach 2 is 0.3 m. By restricting within-day variation in flow, conditions critical for YOY fish in backwater habitats should be protected. Significant attenuation in flow and stage variation (on the order of 50%) occurs between the Jensen gage and Ouray NWR, the area where most backwater nursery habitat exists (Section 3.4.5). Further attenuation occurs downstream, and essentially no fluctuation attributable to hydropower operations can be detected at the Green River gage. Thus, the amount of variation in flow and stage that would occur in the most important habitat areas would be considerably less than our recommended limits.

Cold shock at the Yampa River confluence is a concern for Colorado pikeminnow larvae when they drift in summer from the relatively warm Yampa River into the relatively cold Green River, especially when the Green River is 5ºC or colder (Berry 1988). Therefore, we recommend that the Green River be no more than about 5ºC colder than the Yampa River during summer base-flow conditions. Likelihood of temperature shock should be reduced during dry and moderately dry hydrologic conditions because of the likelihood of achieving target temperatures of 18–20ºC in Lodore Canyon. Releasing water up to 15ºC during average and wetter hydrologic conditions should allow for sufficient downstream warming to reduce the chance of cold shock even though target temperature conditions may not be achieved in all years. These temperature recommendations also may benefit the growth and condition of all life stages of Colorado pikeminnow and humpback chub that may reside in the upper portion of Reach 2.

5.2.3 Recommendations for Reach 3 — White River Confluence to the Colorado River Confluence

Recommended flows for Reach 3 (Table 5.6) are those measured at the USGS gage near Green River, Utah, and are largely dependent on flows targeted for Reach 2 and runoff patterns of tributaries. Major tributaries in Reach 3 are the Duchesne, White, Price, and San Rafael Rivers. These rivers contribute flow and sediment to the Green River, and the timing of inputs will vary among the tributaries in any year because of differences in weather conditions within the drainage basins. Base flows will be subject to natural variation in tributary flows, and this variation should not be compensated for by Flaming Gorge Dam releases.

Peak flows greater than or equal to 623 m^3/s in wet, moderately wet, and average years would inundate floodplain habitats in the upper portion of Reach 3 (White River to upper end of Desolation Canyon). Recommended peak flows also would inundate side-canyon habitats in lower portions of the reach that provide growth and conditioning areas for Colorado pikeminnow and razorback suckers, provide large recirculating eddies utilized by humpback chubs in Desolation and Gray Canyons, and help maintain channel dynamics and perhaps reverse channel narrowing in some areas.

The Green River in lower Reach 3 within Canyonlands National Park is largely isolated from its floodplain because of the vertical accretion of sediment, which has resulted from extended dry-weather periods, flow regulation, and bank stabilization by tamarisk. Because of this isolation, extremely high peak flows are needed for floodplain inundation in this portion of the river. We

Table 5.6.—Flow and temperature recommendations by hydrologic condition for Reach 3 (White River to Colorado River) to benefit endangered fishes in the Green River downstream of Flaming Gorge Dam.[a]

	Hydrologic Condition[b]				
	Wet (0 to 10% Exceedance)	**Moderately Wet (10 to 30% Exceedance)**	**Average (30 to 70% Exceedance)**	**Moderately Dry (70 to 90% Exceedance)**	**Dry (90 to 100% Exceedance)**
SPRING PEAK FLOW					
General recommendation	Peak flows in Reach 3 should be of the magnitude, timing, and duration to provide floodplain inundation, especially in the upper portion of the reach (between the White River confluence and upper end of Desolation Canyon). In all years, peak flows should be of sufficient magnitude and duration to provide at least some in-channel habitat maintenance throughout the reach. No upper limits are placed on recommended peak flows in any hydrologic condition.				
Peak-flow magnitude	$\geq$ 1,104 m^3/s (39,000 cfs)	$\geq$ 680 m3/s (24,000 cfs)	$\geq$ 623 m^3/s (22,000 cfs) in 1 of 2 average years	$\geq$ 235 m^3/s (8,300 cfs)	
Peak-flow duration	Flows greater than 680 m^3/s (24,000 cfs) should be maintained for 2 weeks or more, and flows greater than 623 m^3/s (22,000 cfs) for 4 weeks or more.	Flows greater than 623 m^3/s (22,000 cfs) should be maintained for 2 weeks or more.	Flows greater than 623 m^3/s (22,000 cfs) should be maintained for 2 weeks or more in at least 1 of 4 average years.	Flows greater than 235 m^3/s (8,300 cfs) should be maintained for at least 1 week.	Flows greater than 235 m^3/s (8,300 cfs) should be maintained for 2 days or more except in extremely dry years ($\geq$ 98% exceedance).
Peak-flow timing	Timing of peak flow will depend on flows targeted for Reach 2 and on runoff patterns of tributaries in Reach 3.				
Anticipated effects[c]	The anticipated effects of peak flows in Reach 3 for each hydrologic condition are qualitatively similar to those in Reach 2. However, since less floodplain and backwater habitat exists in Reach 3, quantitative differences in the effect of peak flows are expected. Benefits of overbank flooding to razorback suckers are expected to be most important in the upper portions of the reach (between the White River and upper end of Desolation Canyon) where most floodplain inundation will occur. Flooded off-channel habitats will benefit young Colorado pikeminnow and razorback suckers in lower Reach 3 and humpback chub in Desolation and Gray Canyons.				

Table 5.6.—Continued.

	Hydrologic Condition[b]				
	Wet (0 to 10% Exceedance)	**Moderately Wet (10 to 30% Exceedance)**	**Average (30 to 70% Exceedance)**	**Moderately Dry (70 to 90% Exceedance)**	**Dry (90 to 100% Exceedance)**
SUMMER THROUGH WINTER BASE FLOW					
General recommendation	Rate of decline from peak flow to base flow should be gradual but will depend largely on rates of decline in tributary flows. Base flow should be reached by early to middle summer (depending on hydrologic conditions) and maintained through February. Actual base flows in Reach 3 will depend on flows targeted for Reach 2 and contributions from intervening tributaries.				
Mean base flow magnitude[d]	92 to 133 m^3/s (3,200 to 4,700 cfs)	76 to 133 m^3/s (2,700 to 4,700 cfs)	52 to 119 m^3/s (1,800 to 4,200 cfs)	42 to 95 m^3/s (1,500 to 3,400 cfs)	38 to 72 m^3/s (1,300 to 2,600 cfs)
Rate of decline from peak flow to base flow	Rate of decline will depend on rates of decline in tributary flows and recommended rates of decline for dam releases (see Table 5.4).				
Base-flow period	About 15 August to 1 March	About 1 August to 1 March	About 15 July to 1 March	About 1 July to 1 March	About 15 June to 1 March
Base-flow variation	No specific recommendations are made for base-flow variation in Reach 3. Seasonal variability around the mean base flow during the base-flow period will depend largely on flows in Reach 2 and flows from tributaries. Within-day variability around the base flow will depend largely on tributary flow patterns.				
Anticipated effects[c]	Gradually declining flows after the spring peak flow will provide reproductive cues to Colorado pikeminnow and humpback chub adults [Sections 4.2.5.1, 4.2.5.2.2, and 4.4.6.2.1; Objective 1].				
	Base flows in summer and autumn scaled to the hydrologic condition favor the formation of backwaters and other low-velocity shoreline nursery habitats [Section 3.6.2; Objective 5].				
	Lower water temperatures at higher base flows in the wettest years may reduce growth and survival of young endangered fish [Sections 4.2.5.2.2, 4.2.5.3, 4.3.5.2.2.1, 4.4.6.2.2.2].		Higher water temperatures at lower base flows will enhance growth and survival of young endangered fish, particularly Colorado pikeminnow and humpback chubs [Sections 4.2.5.2.2, 4.2.5.3, 4.2.5.4, 4.3.5.2.2.1, and 4.4.6.2.2.2; Objective 5].		

Table 5.6.—Continued.

	Hydrologic Condition[b]				
	Wet (0 to 10% Exceedance)	**Moderately Wet (10 to 30% Exceedance)**	**Average (30 to 70% Exceedance)**	**Moderately Dry (70 to 90% Exceedance)**	**Dry (90 to 100% Exceedance)**
SUMMER THROUGH WINTER BASE FLOW (Cont.)					
Anticipated effects[c] (Cont.)	Maintenance of the mean base flow throughout summer, autumn, and winter will promote favorable conditions for the endangered fishes in low-velocity habitats (e.g., backwaters) [Sections 3.6.2, 4.2.5.2.3, 4.2.5.4, 4.3.5.2.1.3, 4.3.5.2.2, 4.3.5.2.3, and 4.4.6.2.2.2; Objective 5].				

[a] Reach 3 is located between the White River confluence (RK 396.2) and the Colorado River confluence (RK 0.0). This reach supports humpback chub populations, contains Colorado pikeminnow spawning areas, and provides nursery habitat for young endangered fish. Reproduction by razorback suckers is suspected in this reach. Recommended flows are those measured at the USGS gage near Green River, Utah.

[b] See text for description of hydrologic conditions.

[c] Numbers in brackets [ ] refer to sections in this or previous chapters that contain information supporting the anticipated effects, and they also refer to objectives achieved by the recommendation (see Table 5.2 for a list of recommendation objectives).

[d] The range of base-flow magnitudes for each hydrologic condition was determined from the range of base flows recommended for Reach 2 (see Table 5.5) and the range of flow inputs from tributaries to Reach 3.

recommend that the magnitude of peak flows in wet years be greater than or equal to 1,104 m^3/s to inundate floodplain habitats in lower Reach 3.

Recommended summer-flow patterns in Reach 3 should produce suitable conditions in backwaters and other low-velocity habitats for the growth and conditioning of young Colorado pikeminnow and humpback chubs in most years (average, moderately dry, and dry). Release fluctuations at Flaming Gorge Dam have little effect on flow patterns in Reach 3.

5.3 EXAMPLES OF RECOMMENDED FLOW PATTERNS IN REPRESENTATIVE YEARS

To illustrate how recommended flow patterns would vary among years with different hydrologic conditions, example hydrographs were developed on the basis of actual runoff volumes for selected past years. Seven representative years were chosen for hydrograph development. One year each was chosen for wet (1983), moderately wet (1980), moderately dry (1981), and dry (1991) hydrologic conditions. Three years were chosen for average hydrologic conditions (1964, 1974, and 1991) to capture the wider range of runoff volume in average years. All of the years chosen for this presentation were years after Flaming Gorge Dam was completed in order to allow a comparison of example flow patterns that follow our recommendations with the flows that actually occurred in these years (recorded flows) and with the flows that would have occurred without regulation. (Unregulated flows were modeled on the basis of measured inflow into Flaming Gorge Dam and tributary contributions.)

To develop an example hydrograph for each representative year that would result from implementing the recommendations, hypothetical Flaming Gorge Dam releases were added to the actual tributary runoff patterns in that year to achieve the specific recommended target peak-flow and base-flow characteristics in Reaches 2 and 3 (magnitude, duration, and timing as identified in Tables 5.4, 5.5, and 5.6). The hydrographs presented here are not the only ones that would meet the recommendations; they should be considered examples of the types of flow conditions that could occur if the recommendations are followed. In any given year, specific information (see Table 5.3) on runoff patterns, flow conditions in the previous year, existing habitat conditions (e.g., sediment deposits, vegetation), fish population characteristics (e.g., appearance of larvae, status of populations), and other factors should be used in developing the specific flow pattern for that year.

In general, the example flow patterns that would have resulted from implementing the recommendations are more similar to unregulated flows than are the actual flows that occurred in each representative year in terms of the magnitude and duration of peak flows and in terms of the mean base flow (Figures 5.3 to 5.9; Table 5.7). In the years examined, flows in Reach 2 that were greater than or equal to 527 m^3/s (floodplain habitat inundation increases substantially in Reach 2 as flows exceed this value) actually occurred in only 2 of the 7 years. Flows greater than or equal to 527 m^3/s would have occurred in 5 of the 7 years without regulation, and in 4 of the 7 years with implementation of our recommendations. In Reach 3, flows that were greater than or equal to

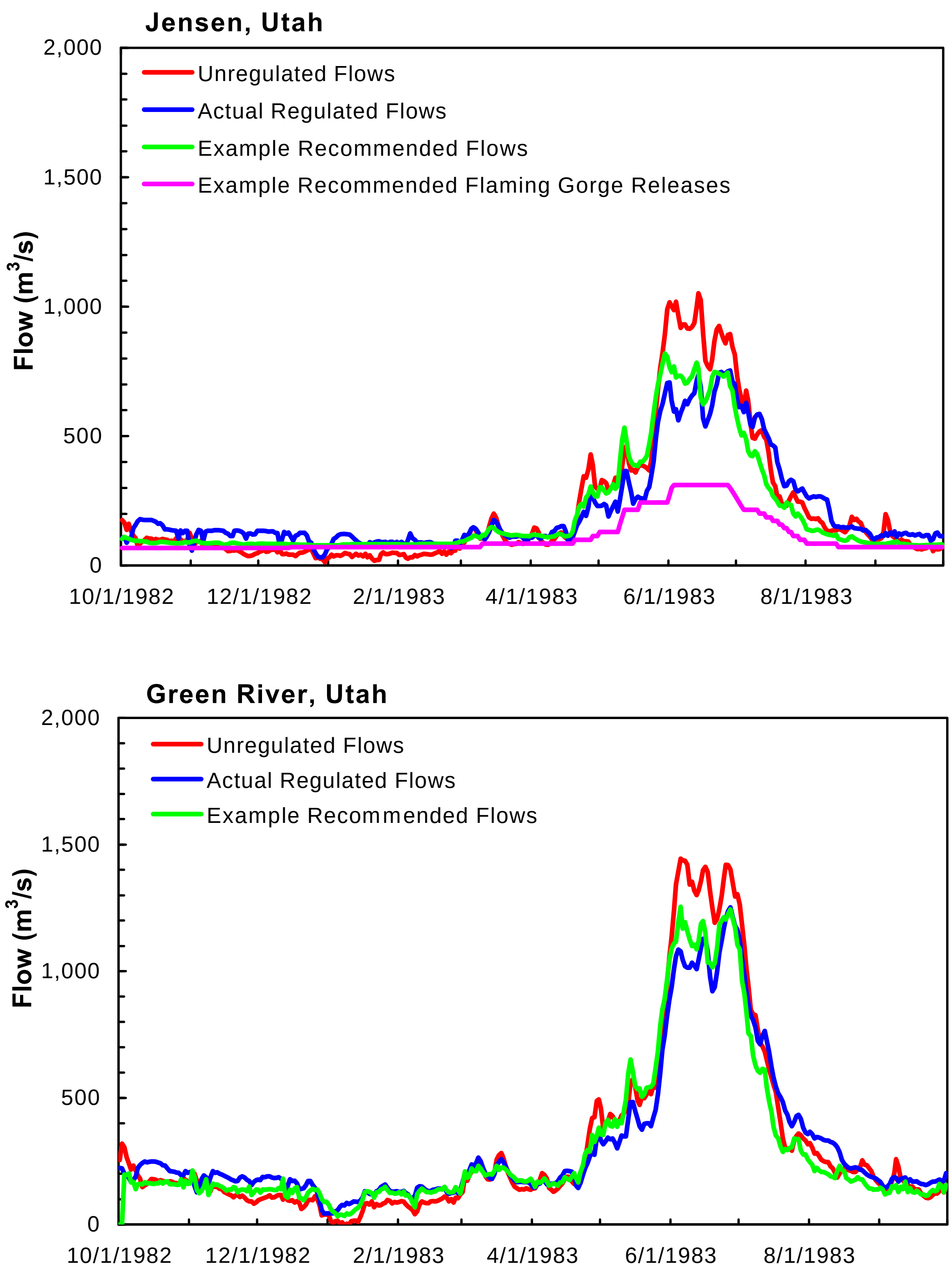


Figure 5.3.—Example recommended flows compared to unregulated and actual regulated flows of the Green River in a representative wet year (1983; 5% exceedance) at the USGS stream gages near Jensen and Green River, Utah.

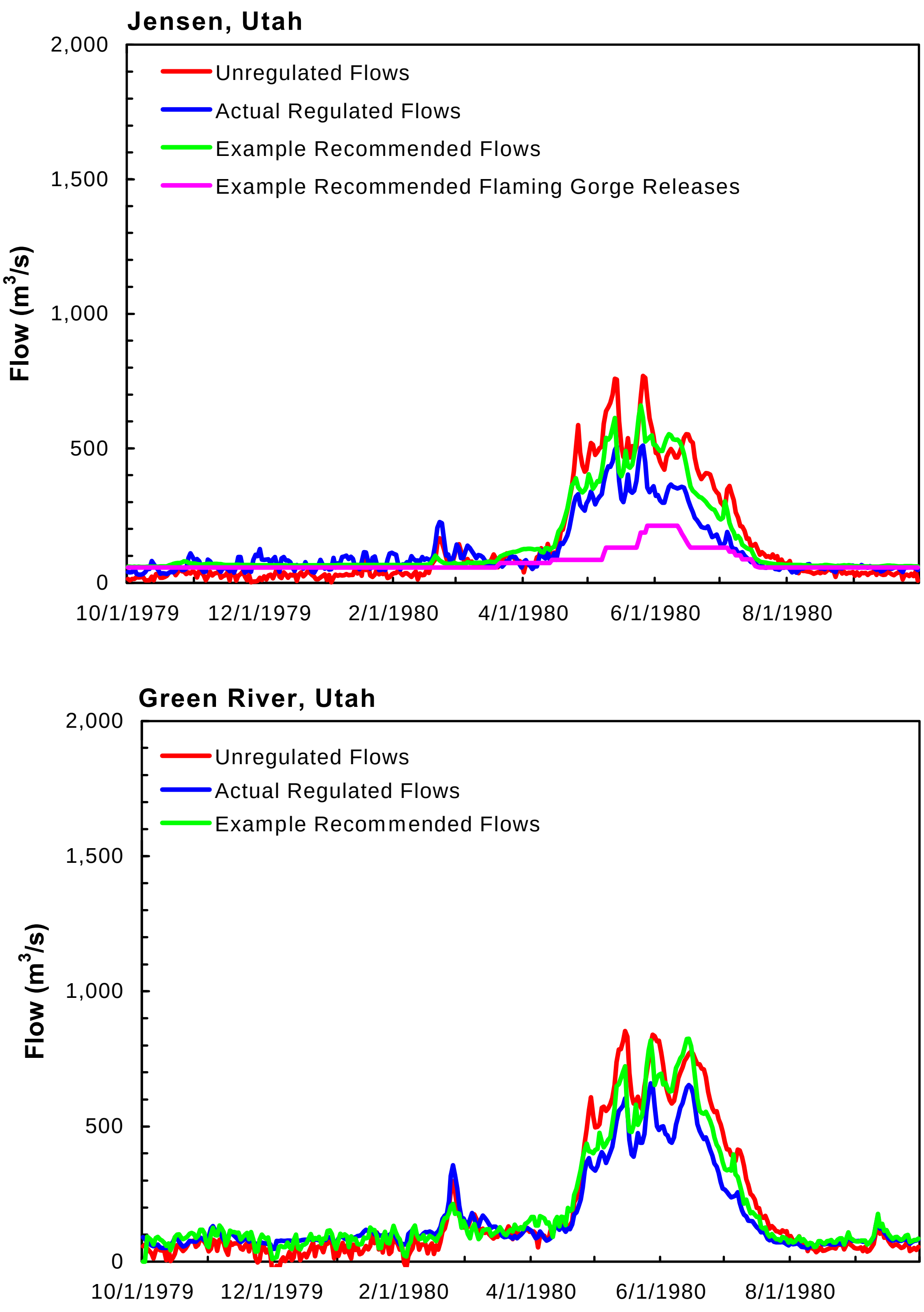
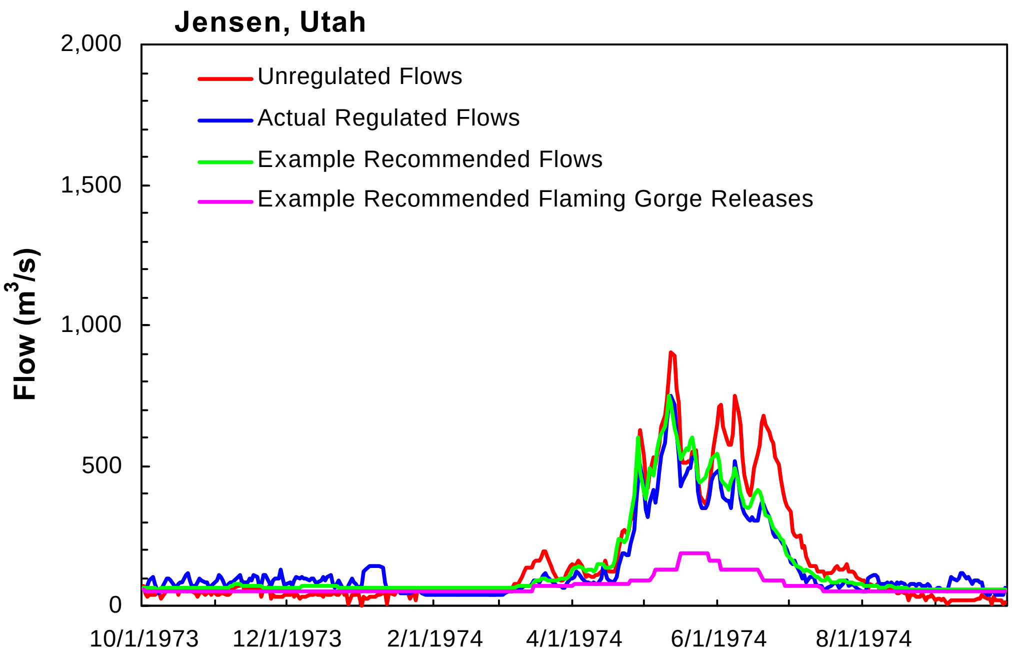


Figure 5.4.—Example recommended flows compared to unregulated and actual regulated flows of the Green River in a representative moderately wet year (1980; 29% exceedance) at the USGS stream gages near Jensen and Green River, Utah.



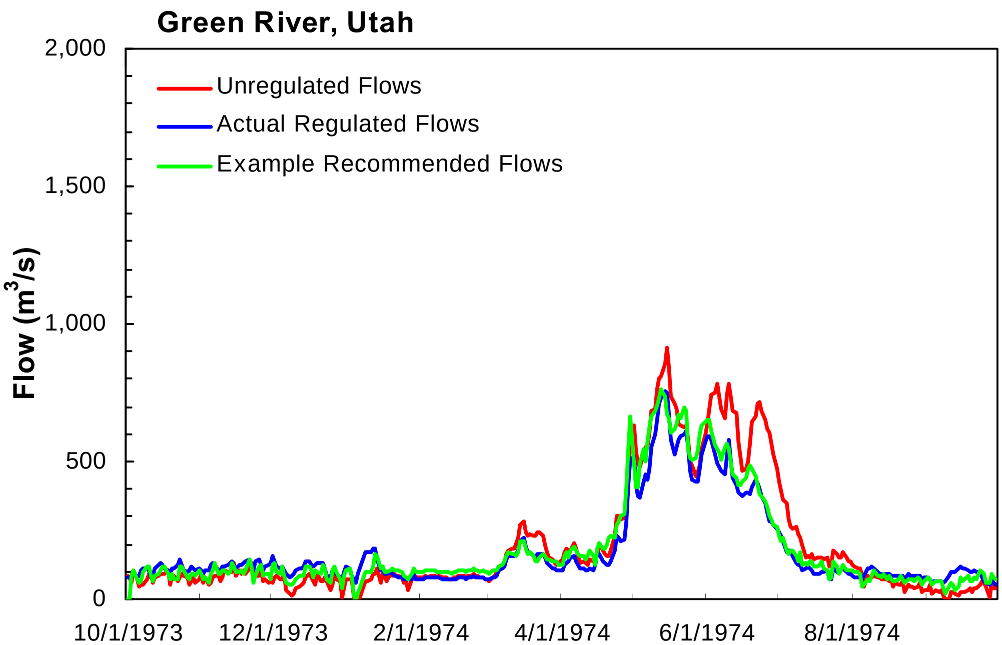


Figure 5.5.—Example recommended flows compared to unregulated and actual regulated flows of the Green River in a representative average year (1974; 32% exceedance) at the USGS stream gages near Jensen and Green River, Utah.

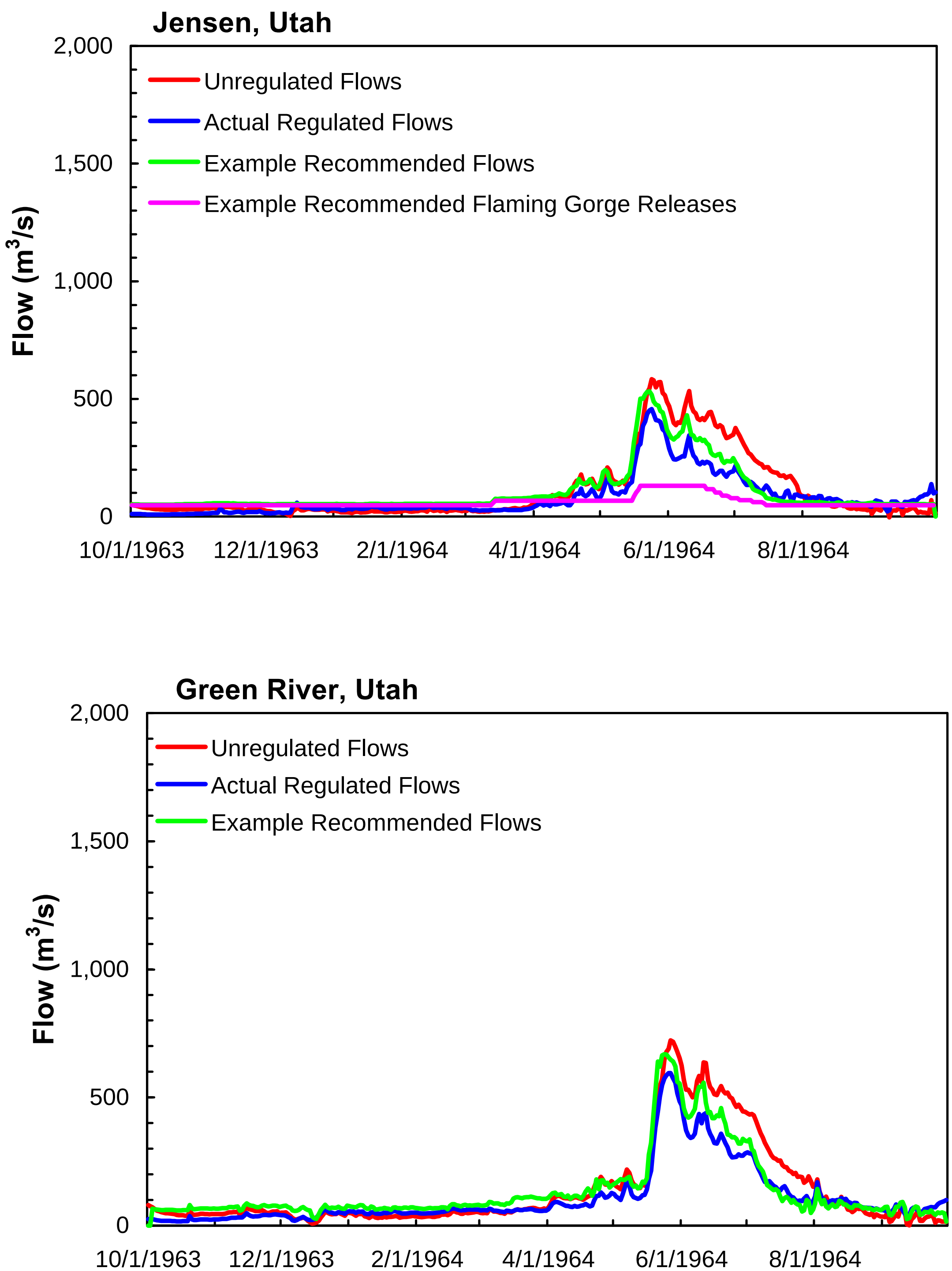


Figure 5.6.—Example recommended flows compared to unregulated and actual regulated flows of the Green River in a representative average year (1964; 43% exceedance) at the USGS stream gages near Jensen and Green River, Utah.

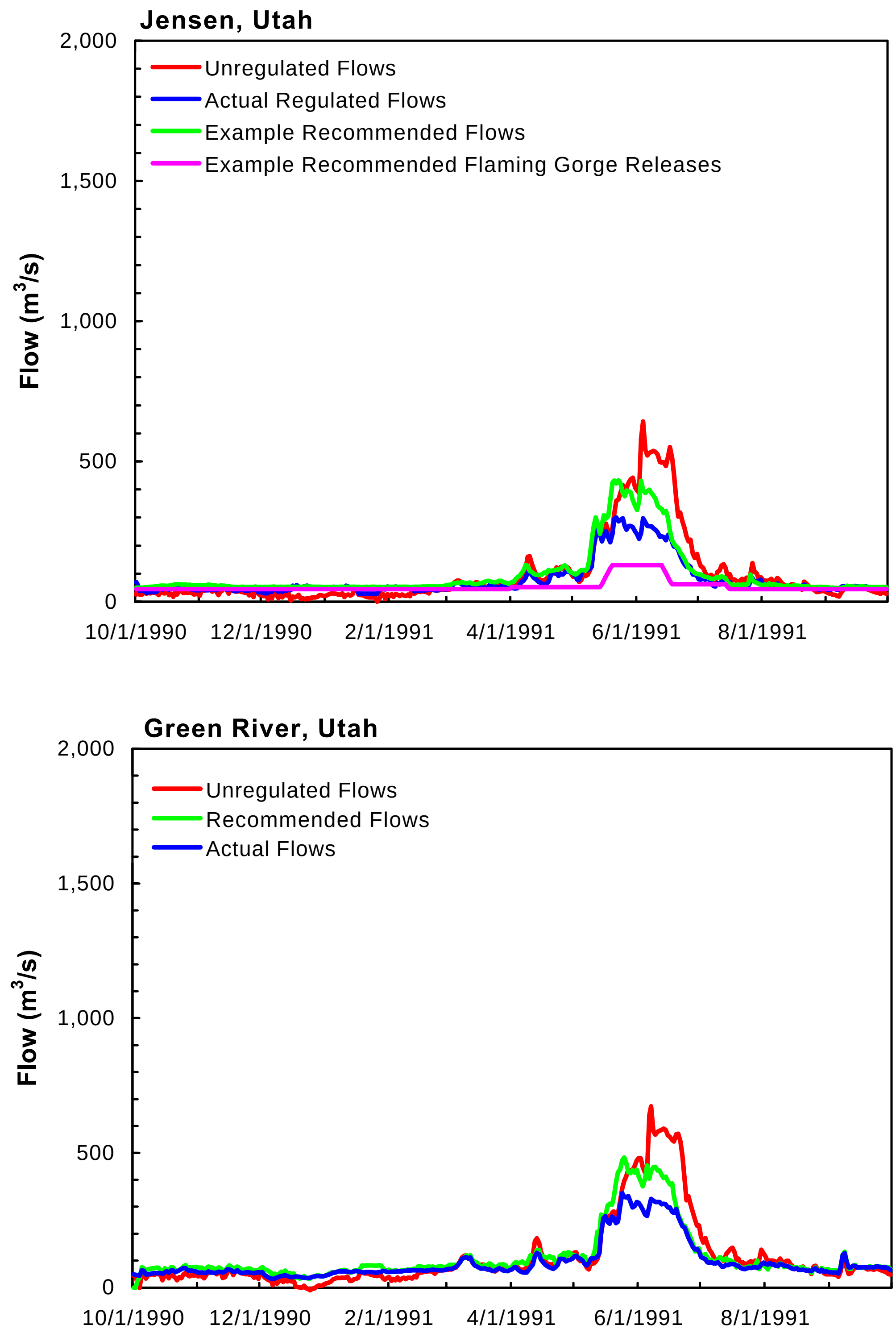


Figure 5.7.—Example recommended flows compared to unregulated and actual regulated flows of the Green River in a representative average year (1991; 62% exceedance) at the USGS stream gages near Jensen and Green River, Utah.

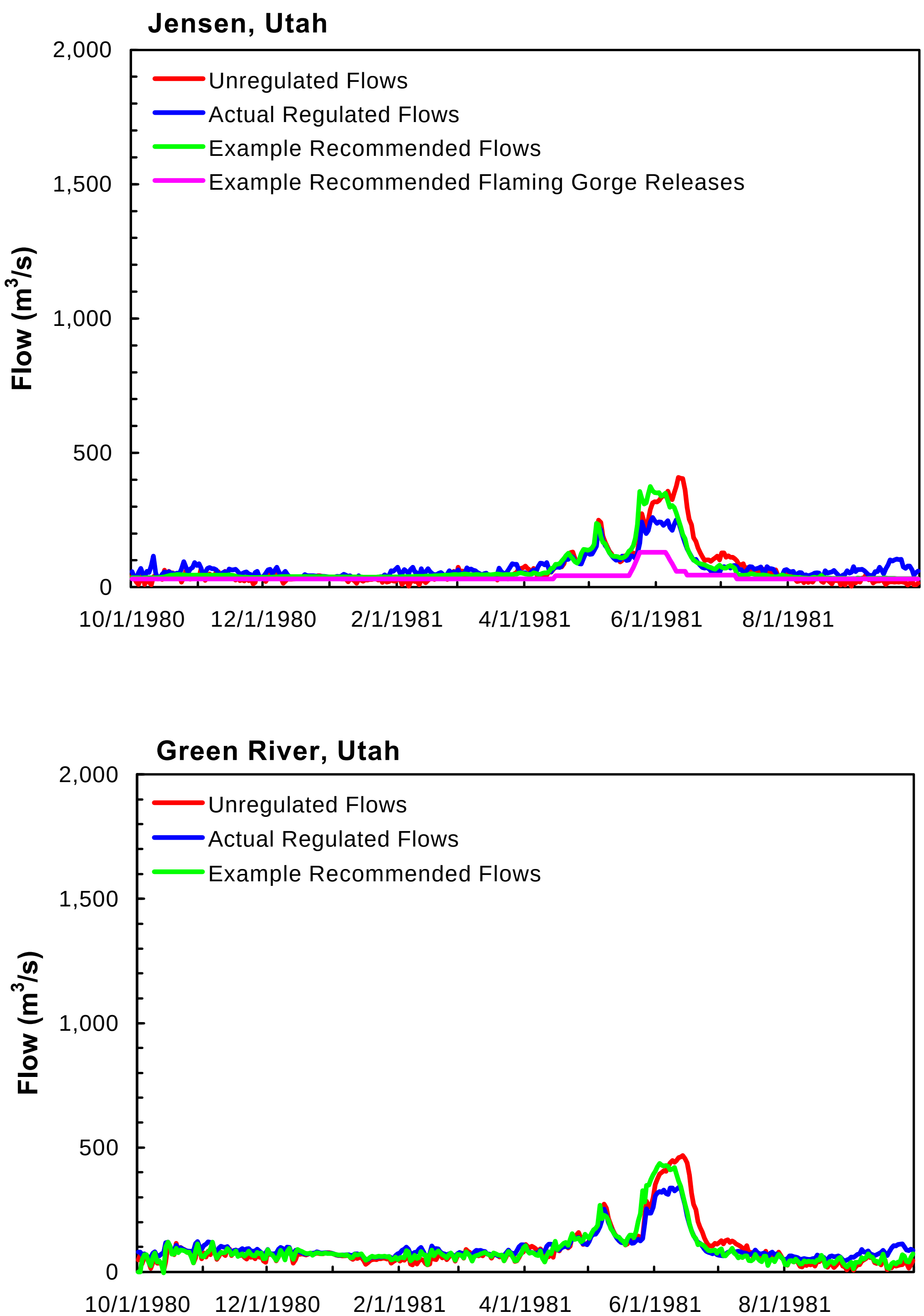


Figure 5.8.—Example recommended flows compared to unregulated and actual regulated flows of the Green River in a representative moderately dry year (1981; 89% exceedance) at the USGS stream gages near Jensen and Green River, Utah.

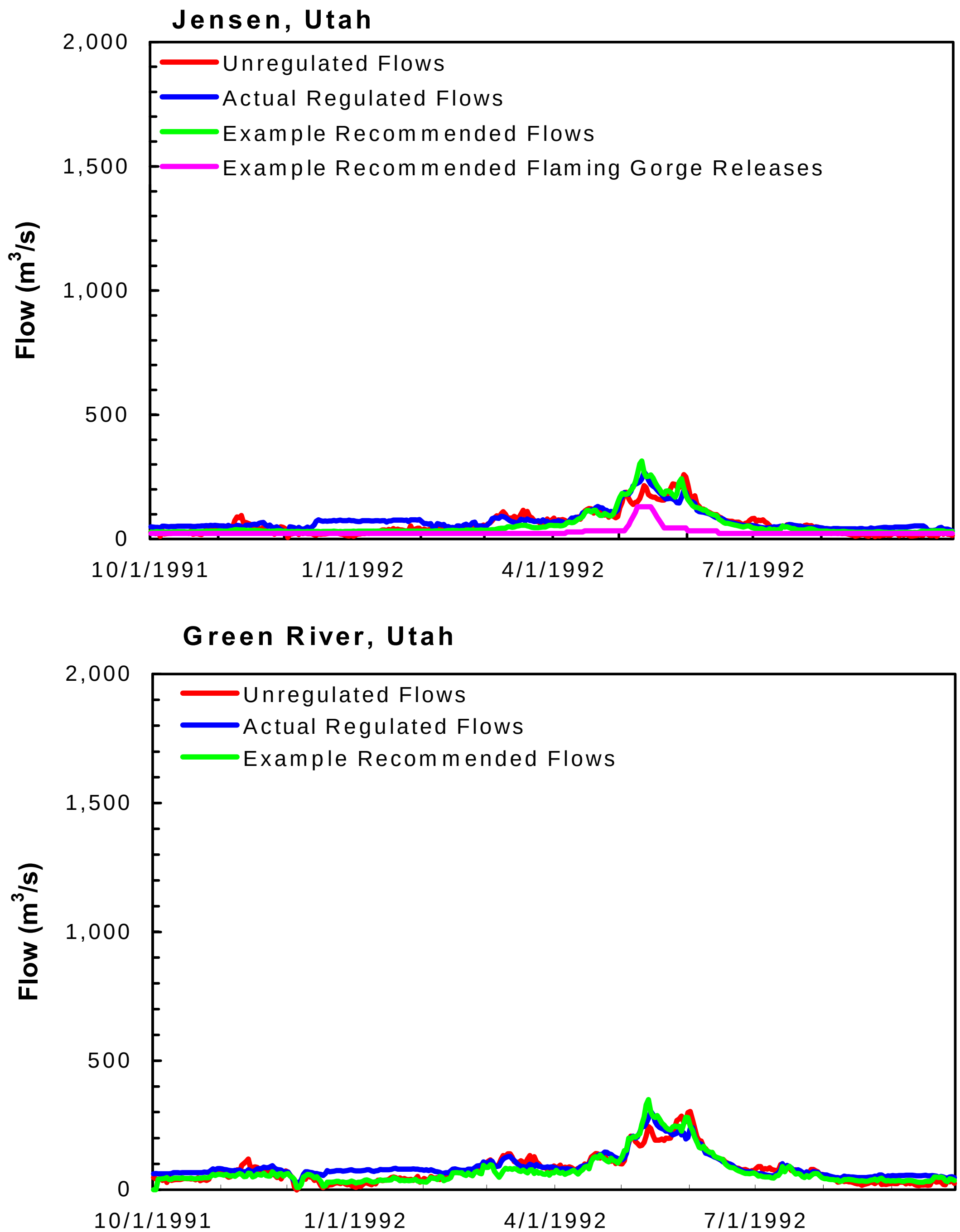


Figure 5.9.—Example recommended flows compared to unregulated and actual regulated flows of the Green River in a representative dry year (1992; 96% exceedance) at the USGS stream gages near Jensen and Green River, Utah.

Table 5.7.—Comparison of flow recommendations for representative example years to actual releases from Flaming Gorge Dam and unregulated and actual Green River flows at the USGS stream gages near Jensen and Green River, Utah.

	Flaming Gorge Release		Flows at Jensen			Flows at Green River		
Parameter	Flow Recom-mendations[a]	Actual[b]	Unregulated[c]	Flow Recom-mendations[d]	Actual[e]	Unregulated[f]	Flow Recom-mendations[g]	Actual[h]
WET (1983; 5% EXCEEDANCE)[i]								
Peak flow (m^3/s)	311	348	1,052 38 d > 643 43 d > 527	790 32 d > 643 39 d > 527	753 19 d > 643 48 d > 527	1,444 46 d > 680 48 d > 623	1,214 41 d > 680 45 d > 623	1,252 48 d > 680 49 d > 623
Mean base flow (m^3/s)	71	100	79	88	122	133	140	175
MODERATELY WET (1980; 29% EXCEEDANCE)[i]								
Peak flow (m^3/s)	212	113	769 9 d > 643 22 d > 527	660 1 d > 643 18 d > 527	510	853 29 d > 680 36 d > 623	824 17 d > 680 29 d > 623	660 5 d > 623
Mean base flow (m^3/s)	59	54	36	69	68	58	91	90
AVERAGE (1974; 32% EXCEEDANCE)[i]								
Peak flow (m^3/s)	187	125	906 16 d > 643 39 d > 527	746 3 d > 643 18 d > 527	748 4 d > 643 9 d > 527	911 24 d > 680 35 d > 623	760 7 d > 680 18 d > 623	759 4 d > 680 6 d > 623
Mean base flow (m^3/s)	54	61	42	64	75	67	88	99
AVERAGE (1964; 43% EXCEEDANCE)[i]								
Peak flow (m^3/s)	130	101	584 8 d > 527	533 2 d > 527	456	722 4 d > 680 11 d > 623	669 7 d > 623	595
Mean base flow (m^3/s)	51	29	31	57	38	47	71	51
AVERAGE (1991; 62% EXCEEDANCE)[i]								
Peak flow (m^3/s)	130	61	642 8 d > 527	432	300	673 2 d > 623	483	351
Mean base flow (m^3/s)	48	36	34	57	46	48	71	61

Table 5.7.—Continued.

Parameter	Flaming Gorge Release: Flow Recommendations[a]	Flaming Gorge Release: Actual[b]	Flows at Jensen: Unregulated[c]	Flows at Jensen: Flow Recommendations[d]	Flows at Jensen: Actual[e]	Flows at Green River: Unregulated[f]	Flows at Green River: Flow Recommendations[g]	Flows at Green River: Actual[h]
MODERATELY DRY (1981; 89% EXCEEDANCE)[i]								
Peak flow (m^3/s)	130	101	410	375	259	468	436	340
Mean base flow (m^3/s)	34	44	31	41	54	54	64	77
DRY (1992; 96% EXCEEDANCE)[i]								
Peak flow (m^3/s)	130	122	259	315	270	304	349	303
Mean base flow (m^3/s)	23	46	30	31	54	42	43	66

[a] Example of releases following recommendations that would achieve recommended target flows in Reach 2. Actual releases would be determined on the basis of specific conditions and needs identified in a given year.

[b] Flows recorded at the USGS gage near Greendale, Utah.

[c] Flows modeled from gauged inflows to Flaming Gorge Reservoir and Yampa River flows.

[d] Flows that would result from example Flaming Gorge recommended releases and Yampa River inflows.

[e] Flow measured at the USGS gage near Jensen, Utah.

[f] Flows modeled from gauged inflows to Flaming Gorge Reservoir and inflows from Green River tributaries.

[g] Flows that would result from Flaming Gorge releases and tributary inflows.

[h] Flows measured at the USGS gage near Green River, Utah.

[i] Hydrologic conditions as defined in text; exceedance values are based on actual April to July inflow into Flaming Gorge Reservoir. Years were chosen to be representative of a particular hydrologic condition.

623 m^3/s (floodplain habitat inundation increases substantially in Reach 3 as flows exceed this value) actually occurred in 3 of the 7 years examined. Flows greater than 623 m^3/s would have occurred in 5 of the 7 years without regulation, and in 4 of the 7 years with implementation of our recommendations. Average base flows in the representative years were lowest without regulation, and, in general, the highest base flows occurred during actual operations in those years.

5.4 COMPARISON OF FLOW AND TEMPERATURE RECOMMENDATIONS WITH THE 1992 BIOLOGICAL OPINION

Although the 1992 Biological Opinion (USFWS 1992) called for a more natural hydrograph and temperature regime that contained many of the same elements included in our recommendations, there are important differences between the two sets of recommendations (Table 5.8). The Biological Opinion focused on the needs of Colorado pikeminnow in the middle Green River downstream of the Yampa River confluence and assumed that if those needs were met, the needs of razorback sucker and humpback chub also would be met. This resulted in the omission of some flow considerations, including specific recommendations for Reach 3. Our recommendations target specific life stages of all three endangered fishes in reaches of the Green River between Flaming Gorge Dam and the Colorado River confluence and incorporate interannual hydrologic variability to ensure that the varied needs of the species are met. The most important differences between the two sets of recommendations are the magnitude and duration of spring peaks, the level of variability in peak and base flows between and within years, and winter operations.

The Biological Opinion called for annual maximum power-plant-capacity releases whose duration, not magnitude, was dependent on hydrologic conditions. Our recommended spring releases are at magnitudes and durations specific to targets for floodplain inundation in Reaches 2 and 3 and are based on annual hydrologic conditions. The variability in spring peaks is important in maintaining dynamic in-channel sediment processes and river-floodplain connections.

Our recommendations include base flows that extend over the entire base-flow period of August through February rather than the August through October period of the Biological Opinion. Our recommended base flows vary depending on hydrologic conditions and recognize that interannual variability occurs. We also recognize the considerable within-year variability in base flow that occurs naturally, as a result of changes in weather patterns, and allow for up to a 40% deviation from the mean base flow within a year.

With our recommendations, hydropower-induced stage changes would be limited to 0.1 m within a day at the Jensen gage. This level of variation should protect the deeper backwaters (mean depth of 0.3 m) preferred by young Colorado pikeminnow. Rather than directly limiting fluctuations in stage, the Biological Opinion restricted fluctuations in flow to a fixed percentage (25%) of the target base flow. This slightly different approach produces some differences between our recommendations and the Biological Opinion in the amount of variability that could occur under different hydrologic conditions. With average hydrologic conditions (target base flow of 51 m^3/s),

Table 5.8.—Comparison of flow and temperature recommendations with the 1992 Biological Opinion on operation of Flaming Gorge Dam for Reaches 1 and 2 of the Green River.[a]

	Reach 1		Reach 2	
	Recommendations[b]	**1992 Biological Opinion**[b]	**Recommendations**[b]	**1992 Biological Opinion**[b]
SPRING PEAK FLOW				
Magnitude	130 to greater than 244 m^3/s, depending on hydrologic conditions, to achieve recommended peak-flow magnitude in Reaches 2 and 3 and maintain adult Colorado pikeminnow habitat in Lodore Canyon of Reach 1.	113 to 133 m^3/s to achieve recommended peak-flow magnitude in Reach 2.	235 to greater than 748 m^3/s depending on hydrologic conditions.	368 to 509 m^3/s.
Duration	Sufficient to achieve recommended peak-flow duration in Reaches 2 and 3.	1 to 6 weeks to achieve recommended peak-flow duration in Reach 2.	2 days to 4 weeks or more depending on hydrologic conditions.	1 to 6 weeks depending on hydrologic conditions.
Timing	Coincident with peak and immediate post-peak spring flows in the Yampa River.	15 May to 1 June, coincident with spring peak flow in the Yampa River.[c]	Coincident with peak and immediate post-peak spring flows in the Yampa River.	15 May to 1 June, coincident with spring peak flow in the Yampa River.
SUMMER THROUGH WINTER BASE FLOW				
Magnitude	Summer through winter: 23 to 76 m^3/s depending on hydrologic conditions.	Not specified.	Summer through winter: 26 to 85 m^3/s depending on hydrologic conditions.	Summer: 31 to 51 m^3/s depending on hydrologic conditions. Autumn: 31 to 68 m^3/s depending on hydrologic conditions. Winter: Not specified.
Onset	15 June to 15 August depending on hydrologic conditions.	Not specified.	15 June to 15 August depending on hydrologic conditions.	20 June to 20 July depending on hydrologic conditions.

Table 5.8.—Continued.

	Reach 1		Reach 2	
	Recommendations[b]	**1992 Biological Opinion**[b]	**Recommendations**[b]	**1992 Biological Opinion**[b]
SUMMER THROUGH WINTER BASE FLOW (Cont.)				
Variation	Not specified.	Not specified.	Summer through winter: Within-day variation resulting from hydropower generation limited to no more than a 0.1-m stage change; variation in mean daily flows no more than 40% of the target base flow.	Summer through autumn: Within-day variation limited to 25% (± 12.5%) of target base flow. Winter: Stable flows after ice cover forms; limit within-day variation if possible. No variation in mean daily flow during the base-flow period.
Water temperature	18ºC or greater for 2 to 5 weeks in upper Lodore Canyon beginning at onset of base flow.	Release warmest water available (approaching 15ºC) from dam in July through October.	Green River no more than about 5ºC colder than Yampa River at their confluence during the summer base-flow period.	Green River no more than 5ºC different from Yampa River at their confluence from 1 July to 1 August.

[a] River reaches: (1) Flaming Gorge Dam to Yampa River confluence, (2) Yampa River confluence to White River confluence, and (3) White River confluence to Colorado River confluence. Recommended flows for Reach 1 are those measured at the USGS stream gage near Greendale, Utah; recommended flows for Reach 2 are those measured at the USGS gage near Jensen, Utah. The 1992 Biological Opinion did not include specific recommendations for Reach 3.

[b] See Tables 5.4 and 5.5 for details on the flow and temperature recommendations; see Section 1.3 for details on the 1992 Biological Opinion.

[c] The 1992 Biological Opinion specified that, if necessary to alleviate storage problems in Flaming Gorge Reservoir, bypass releases from the dam should occur during or before the spring peak of the Yampa River.

our recommended 0.1-m stage change restriction and the Biological Opinion's 25% flow change restriction would produce very similar results. However, in dry years (target base flow of 26 m^3/s), the Biological Opinion restriction would produce a smaller change in stage (about 0.08 m); in wet years (target base flow of 85 m^3/s), it would produce a larger change in stage (about 0.15 m). It should be noted that the level of fluctuations that fully protect low-velocity habitats is uncertain and requires further study (Section 5.5).

The Biological Opinion allowed reservoir-management concerns to dictate releases during winter and did not restrict operations unless an ice cover formed; steady releases were recommended once ice cover formed. Target flows for the winter period were not established in the Biological Opinion. Our recommendations call for a continuation of the summer and autumn target base flow and variability restrictions through the winter regardless of the presence or absence of an ice cover.

Similar to the Biological Opinion, we recommend releasing warmer water from Flaming Gorge Dam in summer to achieve downstream temperature targets. We target water temperatures of 18°C or greater for 2 to 5 weeks in upper Lodore Canyon beginning at the onset of base flow. We recommend that the temperature of the Green River be no more than about 5°C colder than the Yampa River at their confluence during the summer base-flow period to prevent cold shock to drifting Colorado pikeminnow larvae. The Biological Opinion called for no more than a 5°C difference between the Green and Yampa Rivers at their confluence during July.

5.5 UNCERTAINTIES

Our flow and temperature recommendations have some uncertainty associated with them. We do know that present conditions do not meet at least some life-history requirements of the endangered fishes. Modifications of the Green River system have simplified and reduced available habitat, reduced spatial and temporal variability, and changed ecosystem structure and functioning. A paradigm in river management suggests that the ecological integrity of river ecosystems is linked to their natural dynamic character (Stanford et al. 1996; Poff et al. 1997) and that restoring a more natural flow regime to an impaired system is the cornerstone of rehabilitation. However, this paradigm and the response of the endangered fishes of the Green River system are largely untested. As our recommendations are implemented, it is important to be aware of associated uncertainties and plan for managing unanticipated results.

Our recommendations were developed, in part, on the basis of the assumption that future changes in flow, temperature, and sediment regimes of Green River tributaries will be consistent with existing or known pending biological opinions. However, unanticipated changes in current tributary conditions could result from modifications in the operation of existing water projects or from the development of new water projects. Those projects will rely on the Recovery Program to provide reasonable and prudent alternatives. As part of an adaptive management process, the effects of tributary alterations on conditions in the main-stem Green River should be assessed through monitoring, the results of which may necessitate reevaluation of our recommendations.

The physical response of the system to flows is fairly well understood, and the flow recommendations are of the magnitude, duration, and frequency needed to restore much of the dynamic character of the Green River downstream of Flaming Gorge Dam. We assume that restoring physical processes and improving habitat conditions will elicit positive responses from endangered fish populations. For example, evidence suggests that floodplain inundation will improve recruitment of razorback suckers, but this response has not been demonstrated directly. Responses of the endangered fishes to our recommendations will need to be monitored.

Flaming Gorge Reservoir will not have water of sufficient temperature and quantity to achieve our target conditions in Lodore Canyon in all years. Availability will depend on the hydrologic year, season, and climatic conditions. Although warmer water temperatures in Lodore Canyon may be attainable through flow management, target temperatures may not be achieved in wetter years.

Uncertainty exists regarding the responses of nonnative warm-water fishes to our flow and temperature recommendations and subsequent competition or predation effects on the endangered fishes. Warming of release water may result in expansion of nonnative fishes in Reach 1, an area where their abundance is now comparatively low. Although there is some indication that high spring flows have a negative effect on nonnative fish populations (especially in Reach 3), they will likely benefit from the warm-water floodplain habitats that will be created from overbank flooding. Monitoring the responses of nonnative fishes to our flow recommendations will be needed to ensure benefits to the endangered fishes.

There is uncertainty associated with our base flow recommendations. Base flows that optimize conditions for endangered fishes will likely vary from year to year because of the effect of antecedent conditions on sediment processes and habitat conditions. It is known that higher spring flows can produce sediment deposits at higher elevations, behind which backwater nursery habitats form. However, the exact flow level at which backwater habitat conditions are optimized in any given year cannot be easily predicted. To incorporate the effects of antecedent conditions, our recommended mean annual base flows are tied to the hydrologic conditions and the magnitude of the spring peak flow. Although the range of recommended base flows incorporates the range shown by studies to produce suitable backwater conditions, studies of habitat conditions have not been conducted at very low flows.

Effects of base-flow variation on backwater quality are unknown. Variability in base flows occurs at various scales including between years, within a year, between days, and within a day (Section 3.4.3). Natural base-flow variability is a consequence of variation in weather patterns and precipitation events over the period. It is assumed that the endangered fishes of the Green River system are adapted to the recommended level of within-year base-flow variability, which is based on natural, pre-dam values. Although within-day fluctuations may reduce productivity of the food base and growth and survival of native endangered fishes, the effect of these fluctuations on endangered fish populations in Reaches 2 and 3 is not well known. We assume that recommended fluctuation restrictions will protect habitat quality and improve growth, conditioning, and survival of endangered fish. However, the effects of within-day fluctuations on habitat conditions warrant further investigation.

5.6 RESEARCH AND MONITORING NEEDS

In addition to a need to collect real-time biological and physical data each year to refine how our flow and temperature recommendations are implemented (Section 5.2; Table 5.3), there is a need to conduct additional research and long-term monitoring of fish responses to address the uncertainties discussed in Section 5.5. Although it is beyond the scope of this report to provide a detailed description of research and monitoring needs, we suggest that the collection of additional data on endangered fishes and their habitats should focus on the evaluation and possible modification of our recommendations by following an adaptive-management process. Research should be conducted by using carefully designed experiments based on hypothesis testing. Examples of research topics include the effects of fluctuating flows in summer and autumn on the quality of backwaters and the growth and conditioning of endangered fish and the effects of winter conditions (including magnitude of base flows and fluctuation levels) on overwinter fish survival and condition. Monitoring should address such issues as the reproduction and recruitment responses of the endangered fishes to overbank flooding, the effects of spring flows on Colorado pikeminnow recruitment, and the responses of nonnative fish populations to the flow and temperature recommendations. Because the endangered fishes are long-lived, population responses to the recommendations may be observable only over longer time spans. Long-term monitoring should focus on measuring any differences among reaches in the response of populations. The greatest benefit will be accrued if flow and temperature recommendations are based on solid information on the current status of populations, sediment resources, and other relevant ecological factors.

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APPENDIX A:

SUPPORTING INFORMATION ON HYDROLOGY OF THE GREEN RIVER SYSTEM

This appendix provides supporting hydrologic information for other sections of the report. Hydrologic conditions in the Green River drainage basin (A.1) and operations of Flaming Gorge Dam during the research period of 1990 through 1996 (A.2) are described first. The approach used to develop simulated time series of daily stream flows is discussed in Section A.3. These simulated data sets were used to characterize the unregulated hydrology of the upper Green River basin and to determine what effects Flaming Gorge Dam operations and river regulation have had on flows in the middle and lower portions of the Green River.

A.1 HYDROLOGIC CONDITIONS IN THE UPPER GREEN RIVER AND YAMPA RIVER BASINS DURING 1990–1996

This section presents information on hydrologic conditions in the upper Green River and Yampa River basins during the research period of 1990 through 1996. Table A.1 summarizes the April through July water volumes during the research period. A great deal of year-to-year variability in the hydrology is apparent from these data. In the Yampa River basin, there were two dry years (1992 and 1994) and two wet years (1995 and 1996). The upper Green River basin experienced an 8-year drought cycle from 1987 through 1994. Inflows to Flaming Gorge Reservoir were below average in all of these years, with 1992 and 1994 being extremely dry. Because of the drought, significantly less water than normal was released from Flaming Gorge Dam between 1991 and 1994. Since Flaming Gorge Reservoir first filled to capacity in 1972, releases have averaged 1.9 billion m^3/year. During 1991–1994, releases averaged only 1.4 billion m^3/year.

The disparity between the hydrology in the upper Green River and the Yampa River basins should be noted. Hydrologic conditions at the two basins tend to be similar because of their physical proximity. However, for any given year, the hydrology of the two watersheds can be considerably different (Table A.1). For water years (1 October to 30 September) 1993, 1995, and 1996, hydrologic conditions were substantially wetter in the Yampa River basin than in the upper Green River basin. During 1951–1996, the upper Green River basin experienced six wet years (1965, 1971, 1972, 1983, 1984, and 1986). Only three of these years were wet in the Yampa River basin. There were seven dry years in the upper Green River (1960, 1961, 1977, 1981, 1988, 1992, and 1994) during 1951–1966; five of these years were dry in the Yampa River.

Table A.2 shows peak-flow data for the Yampa River and for the Green River near Jensen, Utah. The peak flow of the Yampa River provided the basis of the Green River peak flow at the Jensen gage throughout the research period.

Table A.1.—Summary of water volumes during April–July for each year of the research period.[a]

	Upper Green River, Unregulated			Yampa River		
Water Year	Apr–July Volume (10^6 m^3)	Percent Average	Exceedance Probability	Apr–July Volume (10^6 m^3)	Percent Average	Exceedance Probability
1990	767	55	84	867	55	89
1991	1159	83.00	60	1152	73.00	75
1992	434	31.00	97	724	46.00	94
1993	1291	92.00	52	1903	120.00	29
1994	543	39.00	94	803	50.00	92
1995	1752	125.00	27	2588	164.00	5
1996	1653	118.00	32	2452	155.00	8

[a] Historic data used to create averages and the frequency distribution for the upper Green River were generated by using a combination of data from the USGS gage near Greendale, Utah (1951–1962) and data on unregulated inflows to Flaming Gorge Reservoir (1963–1996). Yampa River data were generated by using the sum of flow values from USGS gages on the Yampa River near Maybell, Colorado, and on the Little Snake River near Lily, Colorado, for 1922–1996. Probability values were developed by using a log Pearson III distribution.

Table A.2.—Summary of peak flows during the research period.[a]

	Yampa River			Green River Near Jensen		
Water Year	Peak Flow (m^3/s)	Percent Average	Exceedance Probability	Peak Flow (m^3/s)	Percent Average	Exceedance Probability
1990	260.0	66	82	275.8	52	92
1991	301.9	76	71	300.2	57	88
1992	198.5	50	93	269.9	51	92
1993	497.8	126	23	566.3	107	38
1994	215.5	55	91	331.3	63	83
1995	519.6	131	19	526.7	100	45
1996	570.9	144	12	623.0	118	29

[a] Peak flows listed are the highest daily average flow for the year. Instantaneous peaks would be slightly higher. Yampa River data were generated by using the sum of the flow values from USGS gages on the Yampa River near Maybell, Colorado, and on the Little Snake River near Lily, Colorado, for 1922–1996. Probability values were developed by using a log Pearson III distribution.

Summer 1994 was much hotter and drier than normal in the Yampa River basin, which resulted in very low flows in late summer and early fall. Flows in the Yampa River fell below 0.3 m^3/s in September. Flow-duration analysis demonstrated that Yampa River flows exceeded 0.3 m^3/s 99.9% of the time. The monthly volume of water for the Yampa River in August was 3.1 million m^3, which is only 9% of the monthly average and a 99% exceedance event. In September, the volume of water was 2.9 million m^3 (14% of the monthly average; 98% exceedance).

The runoff pattern in water year 1995 was also unusual. The weather in early and mid-spring was much cooler than normal, which resulted in very late spring runoff (8 June); the historic median date for peak flow in the Yampa River is 22 May. Flows remained much above normal throughout June and July and into August. Yampa River volumes in July were 380% of the monthly average, and a log Pearson III distribution put this volume as a 0.1% exceedance.

A.2 OPERATIONS OF FLAMING GORGE DAM DURING 1990–1996

A.2.1 Operations during Water Year 1990

The elevation of Flaming Gorge Reservoir at the beginning of water year 1990 was 1,834.7 m, with 3.7 billion m^3 of live storage (79% of capacity). Precipitation in 1990 was much below normal in the upper Green River basin; at the end of the water year, the elevation was 1,835.8 m, with live storage of 3.8 billion m^3 (82% of capacity). Average daily flows in the Green and Yampa[1] Rivers are shown in Figure A.1.

- ***Autumn operations*.—**Releases from Flaming Gorge Dam were moderate during October 1989, and daily releases ranged from 22.7 m^3/s (minimum operating levels[2]) to 75.3 m^3/s. These releases, combined with flows from the Yampa River, produced average daily flows between 31.1 and 85.0 m^3/s at Jensen. Hourly releases fluctuated between 22.7 and 99.1 m^3/s for the first 9 d of October but were reduced for the remainder of the month.

- ***Winter operations*.—**During November through March, releases from Flaming Gorge Dam were maintained at or near 22.7 m^3/s. Little hourly fluctuations occurred on most days in winter.

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[1]Yampa River flows were calculated as the sum of flow values recorded at USGS gages on the Yampa River near Maybell, Colorado, and on the Little Snake River near Lily, Colorado.

[2]A minimum release from Flaming Gorge Dam of 22.7 m^3/s has been established by agreement with the State of Utah to maintain the tailwater trout fishery.

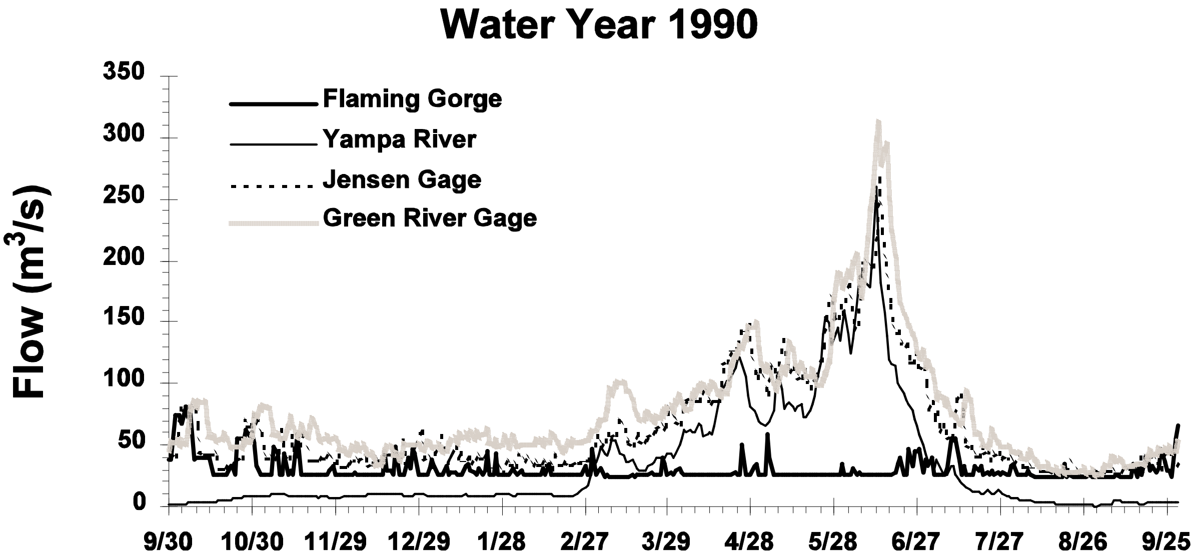

Figure A.1.—Average daily flows in the Green and Yampa Rivers during water year 1990.

- ***Spring operations.***—Because conditions were drier than normal in the upper Green River basin during this year, releases from Flaming Gorge Dam were below normal (below 28.3 m^3/s) and steady from March through July. Occasionally, however, there were days when significant fluctuations occurred, with peak hourly releases up to 113.3 m^3/s. Because water year 1990 was before the issuance of the Flaming Gorge Biological Opinion, a high spring release did not occur.

- ***Summer operations.***—During August and September, the daily average flows at Jensen were near 31.1 m^3/s, while Flaming Gorge Dam releases were maintained at 22.7 m^3/s. Hourly release fluctuations were minimal during the summer.

A.2.2 Operations during Water Year 1991

The elevation of Flaming Gorge Reservoir at the beginning of water year 1991 was 1,835.8 m, with 3.8 billion m^3 of live storage (82% of capacity). Precipitation for the year was near normal in the upper Green River basin; by the end of the water year, the elevation was 1,838.5 m, with live storage of 4.2 billion m^3 (90% of capacity). Average daily flows in the Green and Yampa rivers are shown in Figure A.2.

- ***Autumn operations.***—Releases from Flaming Gorge Dam were moderate during October 1990, and average daily releases generally varied between 22.7 and 45.3 m^3/s.

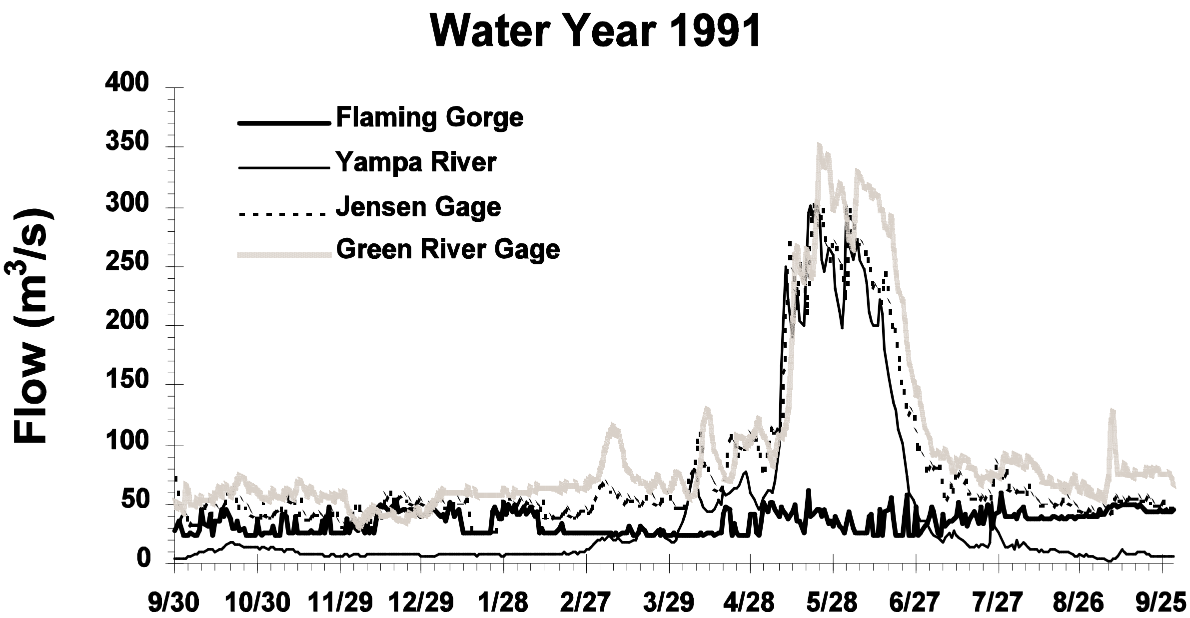

Figure A.2.—Average daily flows in the Green and Yampa Rivers during water year 1991.

Average daily flows in the Green River measured at Jensen ranged between 42.5 and 70.8 m^3/s. Fluctuations in hourly releases were minor during October.

- ***Winter operations.***—During November through March, daily average releases from Flaming Gorge Dam varied between 22.7 and 56.6 m^3/s but were generally maintained near 22.7 m^3/s. From 14 December through 13 January, daily average releases increased to 42.5 m^3/s. Releases were then reduced to 22.7 m^3/s and maintained at that level for the remainder of winter. Hourly fluctuations were minimal on most days. Peak hourly releases for the season reached 70.2 m^3/s on 20 March.

- ***Spring operations.***—Near-normal precipitation was experienced in the upper Green River basin during the year; however, releases from Flaming Gorge Dam were kept near 22.7 m^3/s from March through June. Average daily releases reached a peak of 57.2 m^3/s on 6 June. Hourly releases were ramped on most days to maximize power production and achieve peak-daily releases near 85.0 m^3/s. A high spring release, as later recommended in the Biological Opinion, was not made.

- ***Summer operations.***—During August and September, releases from Flaming Gorge Dam were increased to approximately 42.5 m^3/s. Daily average flows in the Green River measured at Jensen were near 51.0 m^3/s and varied between 42.5 and 65.1 m^3/s. On most days, hourly releases were ramped between 22.7 and 70.8 m^3/s. Daily average flows at

Jensen were near 62.3 m^3/s at the beginning of August, dropped to about 51.0 m^3/s on 7 August, and remained near this level through end of September.

A.2.3 Operations during Water Year 1992

The elevation of Flaming Gorge Reservoir at the beginning of water year 1992 was 1,838.3 m, with 4.2 billion m^3 of live storage (90% of capacity). Precipitation in the upper Green River basin during the year was much below average; at the end of the water year, the elevation was 1,836.0 m, with a live storage of 3.8 billion m^3 (83% of capacity). Average daily flows in the Green and Yampa Rivers are shown in Figure A.3.

- ***Autumn operations.***—During October 1991, releases from Flaming Gorge Dam were made to achieve flows between 38.2 and 51.0 m^3/s in the Green River at the Jensen gage.

- ***Winter operations.***—Reservoir storage was relatively high at the beginning of winter, and there was a need to release water to accommodate forecasted inflows. Releases in December and January were generally about 68.0 m^3/s, but moderate hour-to-hour fluctuations occurred for power generation. On 10 January, for instance, hourly releases varied between 36.8 and 76.5 m^3/s. In February, it became apparent that the upper Green River basin would be very dry during the year, and releases were reduced substantially at this time. Releases in February, March, and April generally were about 42.5 m^3/s, with moderate hour-to-hour fluctuations.

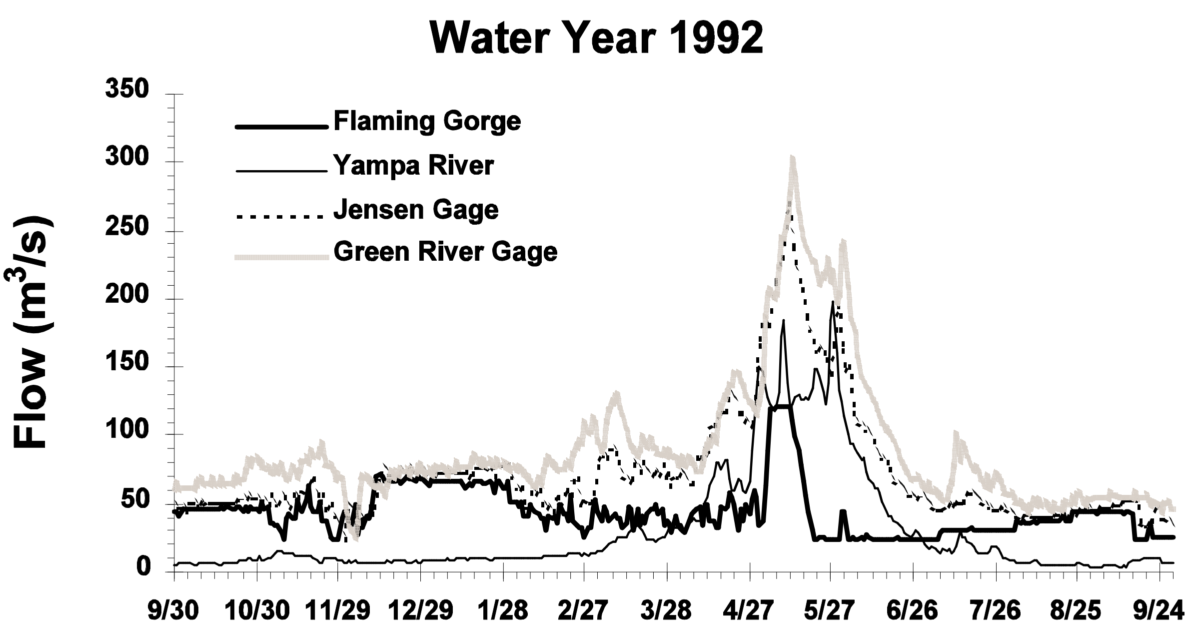

Figure A.3.—Average daily flows in the Green and Yampa Rivers during water year 1992.

- ***Spring operations.***—Because of dry conditions in the upper Green River basin, it was decided that a week-long power-plant-capacity release would satisfy requirements of the Biological Opinion. Releases of approximately 125 m^3/s were made between 6 and 13 May to match the peak flow of the Yampa River. Following this, releases were reduced to the minimum flow of 22.7 m^3/s until the second week of July.

- ***Summer operations.***—A target flow of 45.3 m^3/s at the Jensen gage was maintained during summer. To maintain this flow, releases from Flaming Gorge Dam were adjusted as flows in the Yampa River declined. Hour-to-hour fluctuations at Flaming Gorge Dam were moderated to maintain the ± 12.5% flow deviation constraint at Jensen.

A.2.4 Operations during Water Year 1993

The elevation of Flaming Gorge Reservoir at beginning of water year 1993 was 1,836.0 m, with 3.8 billion m^3 of live storage (83% of capacity). Precipitation during the year was near normal in the Green River basin, but runoff was reduced because of dry conditions in the previous year. At the end of the water year, the reservoir elevation was 1,838.9 m, with a live storage of 4.3 billion m^3 (93% of capacity). Average daily flows in the Green and Yampa rivers are shown in Figure A.4.

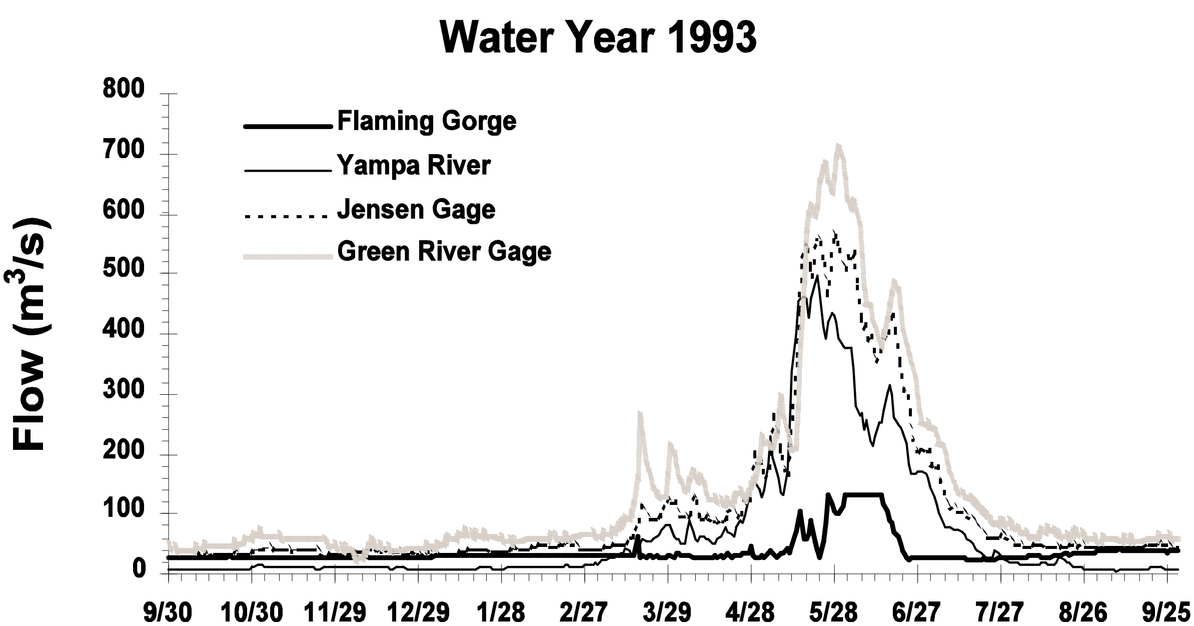

Figure A.4.—Average daily flows in the Green and Yampa Rivers during water year 1993.

- ***Autumn operations.***—Releases were below 25.5 m^3/s every day of October 1992, with the exception of 23 October, when the release was 29.7 m^3/s. No hourly fluctuations occurred. Stable releases from Flaming Gorge Dam combined with flows from the Yampa River produced a stable flow of approximately 34.0 m^3/s at Jensen. Target flows during the previous summer had been higher (45.3 m^3/s).

- ***Winter operations.***—From November through March, releases from Flaming Gorge Dam were approximately 26.9 m^3/s, and hourly fluctuations were relatively small (about 5.7 m^3/s). Because the forecasted April through July inflow was approximately 80% of the average, there was no need to increase winter releases to accommodate high spring inflows into the reservoir.

- ***Spring operations.***—Near-normal hydrologic conditions were experienced during winter, and it was decided that a 4-week power-plant-capacity release of 121.8 m^3/s would be made to meet requirements of the Biological Opinion. This release was scheduled to match the peak flow of the Yampa River. In April, it was expected that the Yampa River would peak at about 396.4 m^3/s, resulting in a combined flow of approximately 509.7 m^3/s at Jensen. A ramp-up rate of 21.2 m^3/s per day from Flaming Gorge Dam, beginning on 14 May, was selected as a transition to the 121.8 m^3/s.

  On 17 May, Reclamation began receiving calls reporting flooding in the vicinity of Jensen. At this time, releases from Flaming Gorge Dam were 96.3 m^3/s, and the flow at Jensen was 523.9 m^3/s. Reclamation, the Service, and Western decided to reduce releases from Flaming Gorge Dam to 51.0 m^3/s to alleviate this flooding. On 20 May, the Service and Reclamation decided that when Yampa River flows were above 396.4 m^3/s, Flaming Gorge Dam would be operated to maintain flows of 509.7–566.3 m^3/s at Jensen. It was thought that this flow would be adequate to accommodate the needs of the endangered fishes while minimizing flooding along the Green River. This operation continued from 20 May to 2 June, when Yampa River flow dropped below 396.4 m^3/s. At this time, release from Flaming Gorge Dam was increased to 121.8 m^3/s. The Yampa River peaked at approximately 509.7 m^3/s on 24 May; the instantaneous peak flow of 574.8 m^3/s at Jensen occurred on 28 May. Beginning on 16 June, Flaming Gorge Dam releases were ramped down at a rate of 11.3 m^3/s per day. Releases reached the minimum of 22.7 m^3/s on 24 June and remained at this level for the remainder of spring.

- ***Summer operations.***—From July through September, Flaming Gorge Dam was operated to maintain a daily target flow of 45.3 m^3/s at the Jensen gage. Minimum releases of 22.7 m^3/s were made during July and the first 5 d of August as Yampa River flows receded. On 6 August, Yampa River flows had declined to 19.8 m^3/s, and Flaming Gorge Dam releases were increased to 25.5 m^3/s to compensate. For the remainder of the water year, daily average releases from Flaming Gorge Dam varied between 25.5 and 35.4 m^3/s to maintain the daily target of 45.3 m^3/s at Jensen. Hourly fluctuations in releases from Flaming Gorge Dam were restricted to maintain instantaneous flows at Jensen between 34.0 and 51.0 m^3/s.

A.2.5 Operations during Water Year 1994

The elevation of Flaming Gorge Reservoir at the beginning of water year 1994 was 1,838.9 m, with 4.3 billion m^3 of live storage (92% of capacity). Precipitation during the year was much below average in the upper Green River basin, and runoff and inflow were further reduced as a result of the dry conditions in previous years. This water year was the eighth consecutive year of below-normal inflow into Flaming Gorge Reservoir. Reservoir elevation was 1,834.1 m at end of the water year, with a live storage of 3.6 billion m^3 (77% of capacity). Average daily flows in the Green and Yampa rivers are shown in Figure A.5.

- ***Autumn operations*.—**During 1–26 October 1993, daily average releases from Flaming Gorge Dam were between 28.3 and 35.4 m^3/s. During 1–10 October, these releases combined with Yampa River flows of about 8.5 m^3/s produced a flow of 45.3 m^3/s at Jensen. Beginning on 11 October, storms in the Yampa River basin caused Yampa River flows to increases significantly. Yampa River flows ranged from 14.2 to 31.1 m^3/s between 11 and 31 October and resulted in flows at Jensen between 51.0 and 71.0 m^3/s. Moderate hourly fluctuations in Flaming Gorge Dam releases occurred in October, but hourly flows at Jensen did not go above or below 12.5% of the mean daily flow at the gage. Beginning on 27 October, releases from Flaming Gorge Dam were increased to transition into winter operation.

- ***Winter operations*.—** From November through March, Flaming Gorge Dam releases were high, with large hourly fluctuations. This operation was chosen on the basis of recommendations from researchers that it would enable them to examine the effects of fluctuating flows on endangered fishes and ice formation. From 0000 to about 0500 hours during this period, releases were held near 22.7 m^3/s. Beginning at 0500 hours, releases were increased until about 0800 hours, when releases reached some midrange value. In the late afternoon or early evening, releases were increased again over a 2-h to 3-h period to high levels (usually around 113.3 m^3/s) and were maintained for about 2–3 h. Beginning at approximately 2000 hours, releases were reduced over a 3-h period to 22.7 m^3/s. Although this general pattern occurred on most days, there were days (especially on weekends) when smaller hour-to-hour fluctuations occurred.

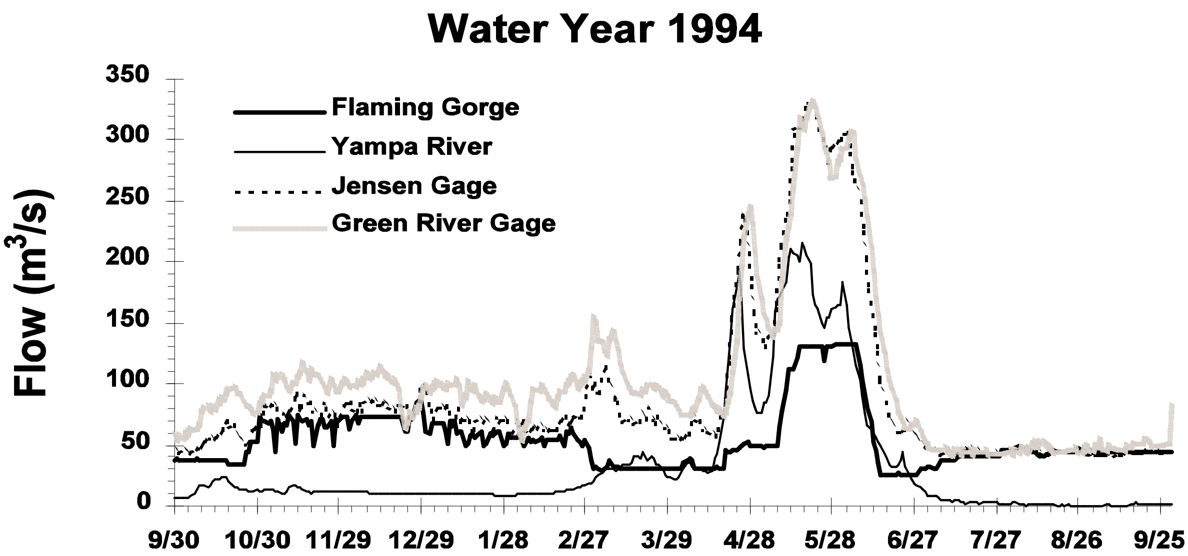

Figure A.5.—Average daily flows in the Green and Yampa Rivers during water year 1994.

The volume of water released from Flaming Gorge Dam during winter varied significantly from month to month. In November and December, 160 and 180 million m^3, respectively, were released from Flaming Gorge Dam. In January, it became apparent that the year would be dry, and Flaming Gorge Dam releases subsequently were decreased to conserve storage. Volumes released from Flaming Gorge Dam in January and February were 149 and 122 million m^3, respectively. To maintain fluctuations and reduce volume, flows in the middle of the day were decreased beginning in January. In November and December, releases between 0800 until 1800 hours were about 79.3 m^3/s. Beginning in January, releases in the middle part of the day were about 45.3 m^3/s. The release pattern remained the same, but the amount of water released during the middle of the day (and thus, total volume) was reduced. In March, the volume of water released was further reduced to a total of 78 million m^3. Minimum releases of 22.7 m^3/s occurred between 2100 and 0400 hours. Generally, a peak release of about 59.5 m^3/s was reached at about 1800 hours.

- ***Spring operations*.**—During 1–20 April, average daily releases from Flaming Gorge Dam were 28.3 m^3/s. Releases were increased to 42.5 m^3/s on 21 April and then to 45.3 m^3/s on 26 April. To comply with the Biological Opinion requirement for a spring peak, researchers recommended that releases be used to maintain relatively high flows at Jensen during spring runoff from the Yampa River basin. These releases were intended to maintain flows of 283.2 to 339.8 m^3/s at Jensen for as long as possible.

A ramp-up of 14.2 m^3/s per day was initiated on 10 May and continued until the maximum power-plant-capacity release of 121.8 m^3/s was reached on 17 May. Maximum power-plant-capacity releases from Flaming Gorge Dam were maintained until combined Green and Yampa River flows dropped below 226.5 m^3/s at Jensen. On 8 June, a 11.3 m^3/s per day ramp-down was initiated, and the minimum release of 22.7 m^3/s was reached on 16 June. During the period of peak spring releases, flows in excess of 283.2 m^3/s at Jensen were maintained for 10 consecutive days (15–24 May) and flows in excess of 226.5 m^3/s were maintained for 27 consecutive days (13 May–8 June).

- ***Summer operations*.—**Flaming Gorge Dam was operated from July to September to maintain a daily target flow of 45.3 m^3/s at the Jensen gage. Minimum releases of 22.7 m^3/s were made from Flaming Gorge Dam during 16–30 June as Yampa River flows decreased. For the duration of the water year, daily average releases from Flaming Gorge Dam were adjusted between 25.5 and 42.5 m^3/s to maintain the Jensen target. Some hourly fluctuation did occur, but the instantaneous flow at Jensen never exceeded 51.0 m^3/s or dropped below 39.6 m^3/s. Very few thunderstorms occurred in the Yampa River basin during this period; consequently, flows in the Yampa River were unusually low.

A.2.6 Operations during Water Year 1995

The elevation of Flaming Gorge Reservoir at the beginning of water year 1995 was 1,834.1 m, with 3.6 billion m^3 of live storage (77% of capacity). Precipitation during the year was above normal in the upper Green River basin. This year was the first since 1986 that inflow was above normal. At end of the year, the elevation was 1,839.0 m, with a live storage of 4.3 billion m^3 (93% of capacity). Average daily flows in the Green and Yampa rivers are shown in Figure A.6.

- ***Autumn operations*.—**During October 1994, daily average releases from Flaming Gorge Dam were about 39.6 m^3/s to maintain a 45.3 m^3/s target flow at Jensen. During 26–31 October, releases were ramped down until a minimum release of 22.7 m^3/s was achieved by 1 November.

- ***Winter operations*.—**From November through March, Flaming Gorge Dam releases were low and steady. Because the previous year had been so dry, the reservoir elevation was low in the beginning of winter, and there was no need to draw down the reservoir; there were no hourly fluctuations in releases. Releases were 22.7 m^3/s during most of November. During late November through the first half of February, daily average releases were 36.8 m^3/s. During the latter part of February and all of March, releases were 22.7 m^3/s.

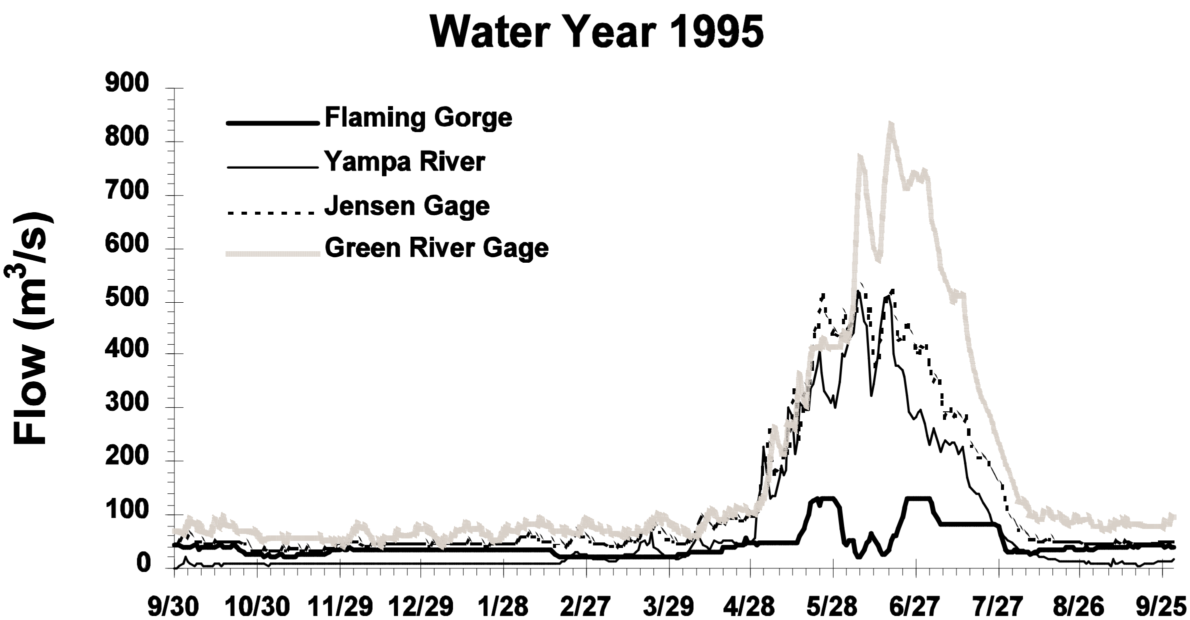

Figure A.6.—Average daily flows in the Green and Yampa Rivers during water year 1995.

- ***Spring operations.***—Releases during the first part of April were 31.1 m^3/s. Releases were then increased to 42.5 m^3/s and maintained until 17 May, when the ramp-up for the high spring release began. Releases were steady during most of April, but moderate hourly fluctuations occurred during May. Snowpack in the upper Green River basin was above normal in 1995, and inflow to Flaming Gorge Reservoir was forecasted to be above normal as the runoff period began. Consequently, a power-plant-capacity release of 130.3 m^3/s was scheduled for 6 weeks, beginning in mid-May.

  Cool, wet weather persisted in both the Yampa and upper Green River basins until the middle of May. These weather conditions increased runoff potential, particularly in the Yampa River basin. The Yampa River was expected to reach a peak flow that, in combination with Flaming Gorge Dam releases, would cause some flooding near Jensen. It was decided that Flaming Gorge Dam releases would be reduced as necessary to prevent flows at Jensen above 509.7 m^3/s. Flaming Gorge Dam releases reached 130.2 m^3/s on 23 May.

- ***Summer operations.***—During July 1995, releases from Flaming Gorge Dam were quite high (85.0 m^3/s) to compensate for the reduced releases in June. In the latter part of July, however, releases were reduced, and a target flow of 51.0 m^3/s at Jensen was established for the remainder of the water year. Daily average releases from Flaming

Gorge Dam during August and September varied between 28.3 and 42.5 m^3/s to achieve the Jensen target flow.

A.2.7 Operations during Water Year 1996

The elevation of Flaming Gorge Reservoir at the beginning of water year 1996 was 1,839.0 m, with 4.3 billion m^3 of live storage (93% of capacity). Precipitation and inflows during the year were above normal. The reservoir elevation was 1,838.1 m at end of the water year, with a live storage of 4.2 billion m^3 (90% of capacity). Average daily flows in the Green and Yampa rivers are shown in Figure A.7.

- ***Autumn operations.***—During October 1995, releases of about 39.6 m^3/s were made to achieve a target flow of 51.0 m^3/s at Jensen.

- ***Winter operations.***—In November, the elevation of Flaming Gorge Reservoir was quite high, and high winter releases were needed to draw down the reservoir. Releases were increased in November to 76.5 m^3/s and maintained until the last week of November, when releases were further increased to 87.8 m^3/s and maintained through December. In January, releases were reduced to 65.1 m^3/s and remained at this level until late February.

  At this time, forecasts of above-average inflow prompted an increase in releases to 73.6 m^3/s, where the releases remained through the end of March.

  Hourly fluctuations occurred in November and December. The daily fluctuation range was generally 45.3 m^3/s. Releases in January and February had no hourly variability. Fluctuations began again in March and were limited to ± 30% of the daily average release.

- ***Spring operations.***—In early April, releases were increased to 87.8 m^3/s. Power-plant-capacity releases of 130.3 m^3/s began on 3 May. They began earlier than in most years because of the need to evacuate water in anticipation of above-normal inflows. Releases of 130.3 m^3/s were maintained until 24 June. In 1996, Reclamation did not reduce Flaming Gorge Dam releases to alleviate flooding near Jensen, as had been done in 1993 and 1995. However, inflow into Flaming Gorge Reservoir was less than forecasted. The reservoir did not fill and reached a peak elevation of 1,838.4 m.

- ***Summer operations.***—From July through September, daily average releases from Flaming Gorge Dam were generally between 36.8 and 48.1 m^3/s to meet the 51.0-m^3/s target flow at Jensen.

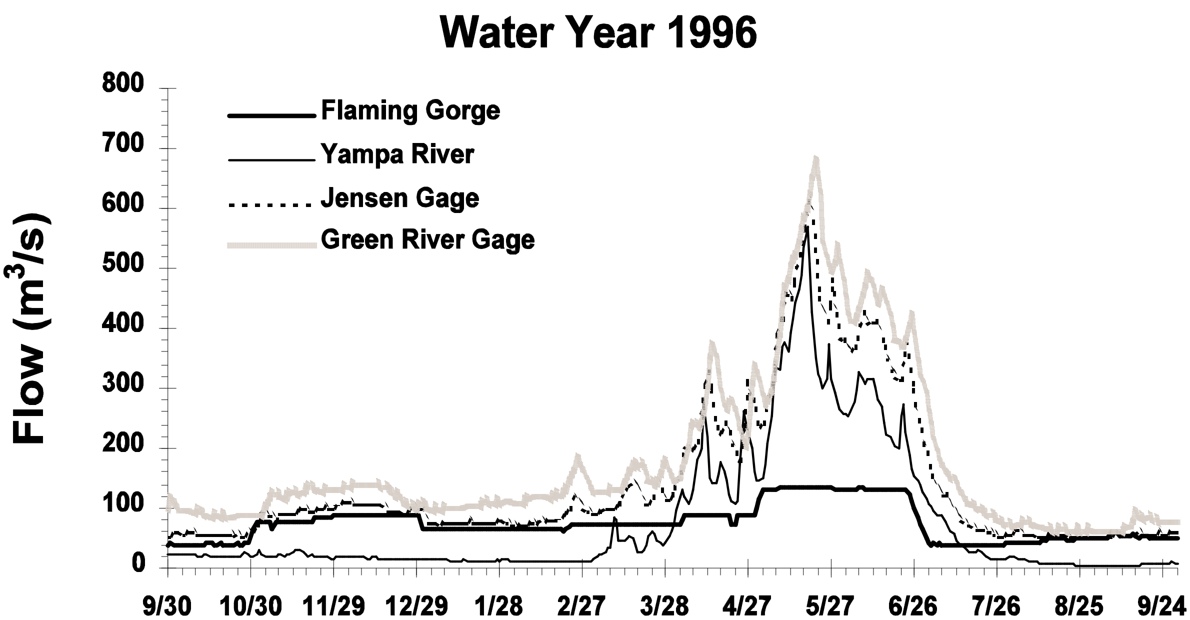

Figure A.7.—Average daily flows in the Green and Yampa Rivers during water year 1996.

A.3 SIMULATION OF DAILY UNREGULATED AND NATURAL STREAM FLOWS IN THE GREEN RIVER BASIN

In characterizing the hydrology of the Green River basin, simulated time series of daily stream flows were developed (Table A.3). These simulated data sets are useful in characterizing the hydrology of the upper Green River basin and numerically determining what effects Flaming Gorge Dam operations and river regulation have had on lows in the middle and lower portions of the Green River. This section describes the approach used to develop these simulated data sets.

A.3.1 Development of Simulated Daily Reservoir Inflows

Before this analysis, data for reservoir inflows for both Fontenelle and Flaming Gorge Reservoirs existed, but these data had been determined by using mass-balance equations that relied on daily changes in reservoir storage to calculate inflow. Such data are very sensitive to measured reservoir elevations and the associated reservoir storage values assigned. Small inconsistencies in measured reservoir elevations result in a very "rough" historic record for reservoir inflow. This roughness is particularly problematic at Flaming Gorge Reservoir, where wind and wave action significantly affect the measured elevation reading.

To create a data set for inflow that does not contain an erratic pattern, an algorithm was developed whereby gauged data above the reservoirs were used to "smooth" the inflow hydrograph.

Table A.3.—Daily flow data sets simulated as part of this investigation.

Site	Data Type	Years
Fontenelle Reservoir	Inflow	1966–1996
Flaming Gorge Reservoir	Inflow	1963–1996
Flaming Gorge Reservoir	Unregulated Inflow	1963–1996
Green River near Jensen, Utah	Unregulated Flow	1963–1996
Green River at Green River, Utah	Unregulated Flow	1963–1996
Green River near Greendale, Utah	Natural Flow	1951–1983
Yampa River near Maybell, Colorado	Natural Flow	1922–1983
Green River near Jensen, Utah	Natural Flow	1947–1983
Duchesne River near Randlette, Utah	Natural Flow	1943–1970
White River near Watson, Utah	Natural Flow	1924–1979
Green River at Green River, Utah	Natural Flow	1906–1970

At Flaming Gorge Dam, two USGS gage sites were used: the Green River near Green River, Wyoming, and Blacks Fork near Little America, Wyoming. For Fontenelle Reservoir, two USGS gages were also used: Fontenelle Creek near Herschler Ranch, Wyoming, and Green River near La Barge, Wyoming. Volumes of the simulated inflows were ratioed so that the volume of inflow in the simulated inflow matched the historic inflow data when compared over a long period of time.

A.3.2 Development of Simulated Daily Unregulated Flows

After the inflow data were simulated, data for unregulated daily flows were simulated. Unregulated flow is the flow that would have occurred at a site in the absence of reservoir regulation upstream. Thus, unregulated stream flow in the Green River near Jensen, Utah, is a simulation of flows that would occur if there were no reservoirs upstream. Unregulated data could be calculated by using historic change-of-storage data at upstream reservoirs. However, this method would result in erratic, unregulated hydrographs in the same way that historic inflow data are subject to sensitivities in readings of reservoir elevations. Therefore, the simulated inflows previously developed were used with historic reservoir releases. The difference between these two data sets (simulated inflow and historic releases) was used to adjust the gauged daily data to generate the simulated unregulated data.

A.3.3 Development of Simulated Daily Natural Flows

Once the simulated unregulated stream flow data were generated, data sets of daily natural stream flow were developed. These were determined by adjusting the flows for depletions due to consumptive use of water and trans-basin diversions. The monthly natural flow database previously developed for use with the Colorado River Simulation System (CRSS) was used. For the years before river regulation, gauged USGS data were adjusted to create the simulated daily natural flows. For years after river regulation, the unregulated flows previously developed were adjusted. Daily values were adjusted by distributing the difference between the monthly natural flow (CRSS data set) and the monthly gauged (or unregulated) flow across the month. In all cases, the natural daily flow was higher than the gauged (or unregulated) flow. This adjustment was minor in winter, whereas in summer, during the irrigation season, the adjustment was much higher.

These simulated data sets were all developed by using computer programs written in the language C. All input and output data (simulated daily stream flows) from these programs were stored in the Upper Colorado Hydrologic Database (HDB). The HDB is a relational database that stores large amounts of hydrologic data.

APPENDIX B:

ABSTRACTS OF SELECTED STUDIES CONDUCTED IN THE GREEN RIVER SYSTEM DURING 1990–1996

Studies abstracted in this appendix include Recovery Program projects conducted under the Flaming Gorge Flow Recommendations Investigation (1990–1996) and other relevant contemporary research that supported findings of this synthesis report. Abstracts were taken unmodified from individual reports when available, but in cases where an abstract was not provided, one was produced based on the contents of the report (those are noted). Abstracts are presented alphabetically by author and chronologically by year.

Allred, T. M., and J. C. Schmidt. 1999. Channel narrowing of the Green River near Green River, Utah: history, rates and processes of narrowing. Final Report of Utah State University Department of Geography and Earth Resources to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 37)

The Green River is the longest tributary of the Colorado River. Near the town of Green River, Utah, the Green River narrowed in 2 discrete phases during the twentieth century. The first phase of narrowing decreased average width by about 5% and occurred between about 1930 and 1940 when the magnitude of the 2-year flood, mean annual discharge, and effective discharge decreased by about 30%, 28% and 37%, respectively. During this first phase of narrowing, saltcedar (*Tamarix* spp.), an invading non-native tree, began to establish itself in the study area, but botanists of that time did not describe the tree as “abundant”. Channel width was stable in the 1940's and 1950's even though saltcedar were becoming abundant on the river’s banks. Further narrowing, of an additional 14%, occurred after 1959. This latest period of narrowing began following 3 successive years when the magnitude of floods was less than the present 1.5-year recurrence flood and when saltcedar was abundant along the river. The deposits that comprise the banks of the narrowing Green River are composed of the suspended load of the river, and these alluvial deposits are characterized by horizontal layers which indicate that they formed by vertical accretion. We propose a mechanism to explain the coarsening upward sequence of beds found in these vertically-accreted deposits.

These changes in the channel of the Green River are based on analysis of more than 2,600 discharge measurements made by the U.S. Geological Survey, resurvey of an abandoned measurement site, matches of historical ground-level photography, and analysis of historical aerial photography within a geographic information system. We have developed analytical techniques that permit analysis of width data from U.S. Geological Survey discharge measurements where gaging cross sections are adjustable. These techniques allow the spatially rich but temporally poor data from aerial photographs to be supplemented with gaging station data which can add detail about the timing and actual processes of channel narrowing that cannot be determined from aerial photographs alone.

Such an analytical strategy provides a more complete record of historical channel adjustment than can be obtained by other means.

Bell, A., D. Berk, and P. Wright. 1998. Green River flooded bottomlands and backwater habitat mapping for two water flows in May 1996 and one water flow in June 1997. Technical Memorandum No. 8260-98-07. U.S. Bureau of Reclamation, Technical Service Center, Denver, Colorado. ***Abstract excerpted from results and conclusions***

Color infrared 1:24,000 scale aerial photography was collected over the Green River on 18 and 20 May 1996, at discharges of 566 m^3/s and 623 m^3/s (as recorded at the USGS gage near Jensen, Utah), respectively. The aerial photography was interpreted to identify, delineate, and estimate areal extent of inundated areas, by land-ownership classes, from Split Mountain to Pariette Draw at each discharge level. Inundation of public land increased 47% and private land inundation increased 84% as discharges increased from 566 m^3/s to 623 m^3/s.

In addition, backwater habitats were mapped from aerial photography taken during low discharge for three locations (near Jensen, Utah; Ouray National Wildlife Refuge, Utah; and Mineral Bottom) along the Green River in October 1993 and in August 1996 and these data were compared to similar mapping done in 1987. For the site near Jensen, Utah, number and total area of backwaters decreased between 1987 and 1993, whereas the average area per backwater increased. Between 1993 and 1996, the number of backwaters increased, but remained less than the number of backwaters identified in 1987. Total area of backwaters and average size of backwaters were greater in 1996 than in 1987.

Within Ouray National Wildlife Refuge, number and total area of backwater habitats decreased from 1987 to 1993. These values increased between 1993 and 1996, but did not reach the levels recorded for 1987. Average backwater size decreased from 1993 to 1996, but the average size of backwaters was greater in 1996 than in 1987.

In the vicinity of Mineral Bottom, the number of backwaters decreased from 1987 to 1993, but the total area and average size of backwaters increased. From 1993 to 1996, the number, average size, and total area of backwaters increased, although differences in the flows at which aerial photography was collected may have complicated the analysis among years for this location.

Bestgen, K. R. 1996. Growth, survival, and starvation resistance of Colorado squawfish larvae. Environmental Biology of Fishes 46:197–209. (Recovery Program Project 12-9)

Growth and survival of Colorado squawfish, *Ptychocheilus lucius,* larvae under fluctuating 18, 22, and 26°C (5°C diel fluctuations) and constant 18, 22, 26°C, and 30°C temperature conditions and ration size corresponding to 12.5, 28, 64, 142, 320 brine shrimp nauplii/fish/day was determined from laboratory experiments. Growth was optimal at 31°C and high at temperatures of 26°C to 30°C, at the highest food abundance. Lowest growth was under lowest food rations and highest temperatures. Growth of Colorado squawfish larvae declined substantially at temperatures < 22ºC. Neither growth nor survival was significantly different between fluctuating or constant regimes. Survival of Colorado squawfish larvae was highest (95%) at 26.2ºC and 235 nauplii/fish/day and high at temperatures of 20 to 30ºC with food abundance > 180 nauplii/fish/day. Survival was lowest when food abundance was low and temperature was high. Highest mortality occurred more than 20 days after experiments began and mortalities occurred sooner in higher than lower temperatures. Colorado squawfish larvae denied food for 5, 10, or 15 d after first feeding could have begun (6 d), had survival greater than 87% which was equivalent to continuously fed controls. Survival of fish denied food for 17.5 d after feeding could have begun declined from 84% before feeding to 57% after feeding. Point of no return was estimated between 17.5 and 20 d. Colorado squawfish have relatively high starvation resistance. Low, stable flows that simulate natural hydrographs may enhance growth, survival, and recruitment of early life stages of Colorado squawfish by increasing water temperature and food abundance in regulated rivers of the Colorado River basin.

Bestgen, K. R. 1997. Interacting effects of physical and biological processes on recruitment of Colorado squawfish. Doctoral Dissertation, Chapter 4. Colorado State University, Fort Collins. (Recovery Program Project 12-9)

Recruitment is central to population ecology because the abundance of young individuals often drives dynamics of subsequent life stages. Recruitment variation of age-0 Colorado squawfish *Ptychocheilus lucius* in the Green River, Colorado River basin, was related to physical and biological factors that were important at both intra-annual and annual time scales. Distributions of squawfish hatching dates derived from otolith increment analyses in 1991 and 1992 indicated that larvae in cohorts that hatched early survived poorly to fall. Growth rate comparisons suggested that the few early-hatched fish that survived were a fast-growing subset of the fish present in the same cohort in summer. I attributed this to a biological factor, size-selective predation mortality by nonnative fishes. In contrast, larvae that hatched late grew relatively slowly but survived at higher rates due to environmental factors and to declines in abundance of predaceous red shiners *Cyprinella lutrensis* by mid-summer. An independent individual-based computer simulation model which had gape-limited red shiners as predators and Colorado squawfish larvae as prey produced similar size-selective survival patterns. Model simulations also showed that fish with moderate growth rates survive at twice the rate of fish with low-growth rates. Growth reductions caused by competition with non-native fishes or starvation would extend the time that Colorado squawfish were susceptible to predation but by themselves would not explain the size-selective patterns observed. Reduced growth rates of Colorado squawfish, which were temporally correlated with a stochastic physical factor, flooding from summer thunderstorms, may have combined with size-selective predation to cause very low recruitment in the lower Green River in 1992. Otherwise, recruitment was not correlated with discharge and temperature regimes in the summers of 1991 and 1992. Over a 17-year record, mean July-August discharge had no effect on annual abundance of Colorado squawfish juveniles in backwaters in the fall except at relatively high discharge. Low abundance of juvenile Colorado squawfish in 1991 and 1992 when size-selective patterns were evident suggested that predation may regulate recruitment in most years. Therefore, discharge management that emphasizes habitat enhancement should be supplemented with strategies to reduce effects of nonnative fishes.

Bestgen, K. R., and M. A. Williams. 1994. Effects of fluctuating and constant temperatures on early development and survival of Colorado squawfish. Transactions of the American Fisheries Society 123:574–579. (Recovery Program Project 12-9)

A laboratory study was conducted to determine the effects of four constant temperatures (18, 22, 26, and 30ºC) and three fluctuating temperatures (diel fluctuations of ± 2.5ºC around 18, 22, and 26ºC) on early development and survival of Colorado squawfish *Ptychocheilus lucius*, which is listed as an endangered species by the U.S. Department of the Interior. Average hatch in constant and fluctuating temperatures was 72% at 18ºC, 67% at 22ºC, 62% at 26ºC, and 38% (constant temperature only) at 30ºC. There was no significant difference in hatch between constant and fluctuating temperatures. Average survival of larvae to 7 d posthatch in constant and fluctuating temperatures was 68% at 18ºC, 64% at 22ºC, 83% at 26ºC, and 13% (constant temperature only) at 30ºC. Survival of larvae at 30ºC may have been confounded by a relatively low hatch of embryos and poor condition of larvae. Survival of larvae was 10–31% higher in fluctuating than in constant temperatures. Incidence of abnormalities was 2–22% at 18–26ºC and 100% at 30ºC. Differences in abnormality rates were not detectable between constant and fluctuating temperatures. Times to start of hatch, swim bladder inflation, and exogenous feeding were shorter at higher temperatures. First feeding occurred about 31 h earlier in fluctuating temperatures than in constant temperatures. Differences in lengths of larvae at hatching and on day 7 posthatch at the venous test temperatures were small and not considered ecologically significant. Tolerance of a relatively wide range of high water temperatures by Colorado squawfish embryos and larvae may reflect the historically variable Colorado River environments in which the species evolved. Low summer water temperatures caused by mainstream dams have eliminated Colorado squawfish from portions of its historic range in the Colorado River basin. Water temperatures that more closely reflect historic regimes are necessary to restore self-sustaining populations of Colorado squawfish in those areas.

Bestgen, K. R., and J. M Bundy. 1998. Environmental factors affect daily increment deposition and otolith growth in young Colorado squawfish. Transactions of the American Fisheries Society 127:105–117. (Recovery Program Project 12-9)

Otolith microstructure of endangered Colorado squawfish *Ptychocheilus lucius* was investigated to determine patterns of otolith growth and to validate daily deposition of increments. Sagittae and lapilli formed prior to hatching. After fish hatched, otolith increments were deposited daily whether larvae were reared at a constant 22ºC temperature or subjected to fluctuating temperatures (± 2.5º/d) centered at 18, 22, or 26ºC. Otolith increments were clearer and counts of increments were more accurate for fish reared at fluctuating than at constant temperatures. Otolith growth was lower at 18ºC than at 22 or 26ºC, but evidence of a direct effect of temperature on otolith growth was inconclusive. Lapillus diameters of slow-growing Colorado squawfish were larger than those of similar-sized but fast-growing fish, indicating that fish and otolith growth rates were not proportional. When larvae were starved, growth in body length generally ceased immediately but otolith growth continued for up to 15 d. Otolith growth was reduced for up to 5 d after starved fish began to feed. Timing of starvation and reduced growth may not be accurately recorded by reduced otolith increment spacing. Low-contrast otolith increments in wild fish may indicate periods of low food abundance and starvation. Increased otolith growth early in life could reflect the start of exogenous feeding by Colorado squawfish larvae, a habitat shift to warmer water, or both. Otolith analysis will be useful for elucidating age, growth, and recruitment patterns of young Colorado squawfish.

Bestgen, K. R., and L. W. Crist. 2000. Response of the Green River fish community to construction and re-regulation of Flaming Gorge Dam. Final Report of Colorado State University Larval Fish Laboratory to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 40)

We evaluated aspects of the protocol offered by Stanford et al. (1996) for restoration of biota in regulated rivers. The chronology of river regulation events and associated biotic evaluations that occurred in the regulated reach of the Green River upstream of the Yampa River from 1962 to 1996 offered an opportunity to determine the effectiveness of thermal enhancement and discharge re-regulation to restore native fishes. Prior to closure of Flaming Gorge Dam, the Green River supported an intact native fish assemblage and few non-native fishes occurred there. Closure and operation of Flaming Gorge Dam eliminated most native fishes in the regulated reach of the Green River from 1967 to 1978 because low water temperatures inhibited reproduction. The hydrograph was flat with no spring peak, high summer base flow, and sediment load was reduced. Thermal enhancement of the regulated reach in 1978, via dam penstock modification, had an immediate effect because reproduction by most resident native fishes was restored. The regulated reach supported nine native fishes, and only rare Colorado pikeminnow and razorback sucker did not reproduce. Discharge re-regulation begun in 1992 partially restored spring peaks and lowered early summer base flows. Sampling conducted during the period 1994 to 1996 demonstrated that native fishes were numerically dominant in electrofishing samples collected in Lodore Canyon. Native fishes were dominant in seine samples collected in upstream Lodore Canyon low-velocity habitats. Roundtail chub was very rare in the reach and may be declining in abundance. Non-native fishes dominated in backwaters in lower Lodore and in Island -Rainbow Park. Populations of other native fishes were stable and abundance of Colorado pikeminnow increased since 1980, perhaps in response to flow re-regulation and subsequent changes in the thermal environment. Abundance of cold water fishes has declined since 1980, and abundance of cool or warm-water fishes increased. Diversity and abundance of non-native fishes increased since 1980, especially in lower Lodore Canyon. Especially problematic may be piscivorous channel catfish, smallmouth bass, and northern pike. A strong water temperature gradient played a large role in controlling distribution and abundance of fishes in the regulated reach during the period 1994-1996. Relatively cool upstream temperatures may have limited the distribution and abundance of several warm-water fishes to reaches of the Green River downstream of lower Lodore Canyon. Limited backwater habitat in the upper reaches of Lodore

Canyon may have restricted occurrence of obligate backwater species such as red and sand shiner, fathead minnow, and redside shiner. Abundance of several combinations of hybrid suckers was high and much increased since 1980. Particularly common were hybrids that had white sucker as one parental type. Occurrence of cool water white suckers and hybrids declined in a downstream direction in Lodore Canyon, presumably in response to warmer water temperatures. Drift net sampling captured few fish of any kind, and reproduction by Colorado pikeminnow was not detected. A moderate-sized population of Colorado pikeminnow inhabited Lodore Canyon and were captured there in spring, summer, and fall. Length changes of recaptured fish and length-mass relationships indicated that resident fish had high growth rates. Minimally, Lodore Canyon provided important habitat for adult feeding. Water temperature of the Green River downstream of Flaming Gorge Dam was reliably predicted by ambient air temperature and discharge level. Water temperatures suitable for reproduction by Colorado pikeminnow were present early in the summer in some years. However, mid- and late-summer warming associated with reproduction by Colorado pikeminnow in the unregulated Yampa River was negated in the regulated reach of the Green River by increased discharge from Flaming Gorge Dam. Increased discharge was mandated by the 1992 Biological Opinion on operation of Flaming Gorge Dam. Further restoration of the fish community and habitat in the regulated reach of the Green River requires re-establishment of more natural discharge and temperature regimes, similar in pattern to those which occur in the unregulated Yampa River and the historical Green River. More natural flow and temperature patterns may also benefit native fishes in Green River reaches downstream of the Yampa River. Distribution and abundance of non-native fish populations will also likely expand if summer water temperatures of the regulated reach of the Green River are enhanced.

Bestgen, K. R., R. T. Muth, and M. A. Trammell. 1998. Downstream transport of Colorado squawfish larvae in the Green River drainage: temporal and spatial variation in abundance and relationships with juvenile recruitment. Final Report of Colorado State University Larval Fish Laboratory to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 32)

This study was initiated in 1990 and was part of the Five-Year Flaming Gorge Flow Recommendations Investigations, 1992-1996. It was designed to assess aspects of reproduction, recruitment, and status of Colorado squawfish in the Green and Yampa Rivers. Colorado squawfish reproduced in early to mid-summer in the Green River basin. Initiation of reproduction by Colorado squawfish each year was generally associated with increasing water temperature and diminishing spring runoff. Earlier spawning was associated with earlier occurrence of peak runoff and warmer water temperatures.

No single variable accurately predicted when Colorado squawfish first reproduce among sites or years. Water temperature at initiation of reproduction ranged from 16.0 to 22.3^{o}C in the lower Yampa River and was 19.8 to 23.0^{o}C in the lower Green River. In the lower Yampa River, Colorado squawfish generally initiated reproduction a few days prior to or within a few days after mean daily water temperature exceeded 18^{o}C. In contrast, Colorado squawfish in the lower Green

River initiated reproduction after mean daily temperature exceeded 18°C for 13 to 39 days. Time of year and accumulated degree days were also reasonable predictors of initiation of reproduction by Colorado squawfish. Initiation of reproduction was not closely associated with days post-peak discharge.

Abundance of larvae was generally higher in the Yampa River than in the lower Green River, and varied widely on diel, spatial, intra-annual and inter-annual scales. High transport abundance of larvae associated with increased turbidity, discharge, and darkness may be due to several factors including loss of orientation. High transport abundance under those conditions may also be a behavioral response to avoid sight-feeding predators. Increased transport abundance during turbidity events may have been caused by increased sediment deposition in interstitial spaces in the substrate, a stress which may have motivated larvae to emerge and drift. Differences in transport abundance of larvae across years and the patterns of abundance within a year may be due to several factors including timing of arrival, condition, and number of reproducing adults at the spawning areas.

Transport abundance appeared to be associated with discharge only during extreme years. High discharge was negatively associated with transport abundance in both the lower Yampa River and the lower Green River while low discharge was negatively associated with transport abundance only at the Yampa River station. Low abundance during either low or high discharge years could be a consequence of low abundance of adults and low production of larvae at spawning areas, high mortality of eggs or larvae at spawning areas or during downstream transport, sampling error, or other factors.

High intra-annual recruitment variation of juvenile Colorado squawfish in both the lower and middle Green River, 1990–1996 was not usually the result of inadequate numbers of larvae produced from spawning areas. Instead, high annual recruitment variation may be a consequence of factors that differentially affect growth and survival of early life stages. Colorado squawfish seem well-adapted to the fluctuating environmental conditions with which they have evolved. Thus, physical factors may regulate recruitment of age-0 Colorado squawfish only in relatively rare instances. Understanding the relative importance of mechanisms regulating recruitment of Colorado squawfish, including effects of discharge, habitat availability, and non-native fishes predators, is critical to management and recovery of this species.

Beyers, D. W., R. T. Muth, and M. S. Farmer. 1994. Experimental evidence of competition between larvae of Colorado squawfish and fathead minnow. Final Report of Colorado State University Larval Fish Laboratory to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado.

Quantitative study of resource competition has been frustrated by an inability to separate effects of intraspecific and interspecific competition. Two types of experimental design are commonly used to study competition in two- species assemblages (1) replacement designs, and

(2) additive designs. We used an experimental design and analysis that incorporated the positive attributes of replacement and additive designs to study resource competition between larvae of federally endangered Colorado squawfish, *Ptychocheilus lucius*, and a widely distributed nonnative species, the fathead minnow, *Pimephales promelas*. Effects of competition were inferred by feeding fish known quantities of zooplankton and comparing relative growth in single- and mixed-species assemblages. Effects of intraspecific exploitative competition were accounted for by using regression to describe the density-dependent relation between relative growth and feeding regime in single-species assemblages, and then subtracting these effects from the response of relative growth in mixed-species assemblages. Relative growth of Colorado squawfish and fathead minnow in single- and mixed-species assemblages was compared using a one-sample t-statistic, regression analysis, and an index of competitive ability. Conclusions of statistical analyses were confirmed by study of diet overlap.

The response of each species to competition was consistent with that predicted by ecological theory: relative growth of both fishes was reduced by competition (i.e., -/-). Negative competitive effects were asymmetrical, and quantitatively greater and more frequent for Colorado squawfish than for fathead minnow. Study of diet overlap confirmed conclusions of relative growth analysis. Diet overlap was reduced in the lowest feeding regime where resource competition was intense. Paradoxically, at higher feeding regimes diet overlap increased although analysis of relative growth suggested competition occurred at those feeding regimes as well. The insensitivity of diet overlap at higher feeding regimes may have been due to a lack of alternative prey, or may suggest that the response variable, relative growth, integrated effects of two qualitatively different competitive mechanisms without reflecting a change because intensity of competition remained relatively constant. These results emphasize the need for more detailed ecological investigations of interactions between early life stages of Colorado squawfish and potential non-native competitors. In addition, this study demonstrated that under experimental conditions, effects of intra- and interspecific competition can be separated and the outcome of exploitative resource competition can be determined.

Chart, T. E., and L. D. Lentsch. 1999. Flow effects on humpback chub (*Gila cypha*) in Westwater Canyon. Final Report of Utah Division of Wildlife Resources to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 46)

This five-year study to determine the effect of Colorado River flows on humpback chub (*Gila cypha*) reproduction and recruitment is a component of the Recovery Implementation Program (RIP) Aspinall Studies. The goal of this project was to develop relationships between observed flows and humpback chub life history responses, concentrating on the earlier life stages. To meet this goal, the following study objectives were identified: determine spawning and nursery requirements, describe the relationship between geomorphic processes of sediment transport and nursery habitat formation, identify and describe reproductive isolating mechanisms, and assess recruitment. Similar research is being conducted on the Green River in Desolation Canyon as part of the Flaming Gorge Studies.

Three components of the Westwater Canyon fish community were studied: the young of year (YOY), juveniles (AGE1+ and 2+) and late juvenile/adults. Both humpback chub (*Gila cypha*) and roundtail chub (*G. robusta*) are common in Westwater Canyon. Unlike some Upper Basin chub populations, the adults of these two *Gila* spp. are morphologically distinct in Westwater Canyon. However, young chubs are difficult to identify to species wherever more than one of these species is found. YOY sampling was therefore broken into sub-reaches: above Westwater Canyon (where only roundtail chubs are common), within Westwater Canyon (roundtail and humpback are equally represented in the adult fish community) and below the canyon (where roundtail chubs are present in low numbers and humpback chub are absent). YOY were sampled with seines. Juvenile chubs were monitored with shoreline electrofishing in the canyon, and late juvenile and adults were sampled with hoop and trammel nets as well as with electrofishing. The design of the study focused on YOY densities (fish/m^2 of seined habitat) and habitat use to establish relationships with observed flows. Juvenile chubs (still not readily identified to species) were monitored in the canyon to take the flow/reproduction relationship to the next step. Only three of the five cohorts produced during this study (1992, 1993, and 1994) could be tracked past their first summer (age 0); the 1995 cohort was virtually non-existent and further monitoring of the 1996 cohort was beyond the scope of this study. Late juvenile and adult chubs were monitored to determine population trend and stability in light of the recent recruitment. Pre-project data were incorporated into these analyses.

Hatching time and growth of young *Gila* spp. were correlated with flow parameters (peak flow at State Line gage and pre-peak flow in excess of 6000 cfs (a cumulative flow metric similar to degree days)) and water temperature (degree days > 10ºC prior to June 15). In general, YOY chubs hatched earlier above the canyon indicating roundtails likely spawned earlier than humpbacks. Catch rates of YOY *Gila* spp. were greatest in the above-canyon sub-reach with a project high density, 0.679, recorded there during July and August of 1993. The greatest density of YOY chubs within Westwater Canyon was nearly as high, 0.673, recorded during the summer of 1996. The catch rates of chubs were significantly higher in the above-canyon and canyon sub-reaches than in the sub-reach below the canyon. Reproductive success as measured by densities of YOY chubs was positively correlated with the previous year's peak flow, and negatively correlated with the amount the June monthly mean flow deviated from the historic monthly mean. The greatest canyon catch rates occurred when the river peaked near 30,000 cfs. A multinomial analysis indicated YOY chubs used backwater habitats as they were available, but did not select for them. Similar use was recorded in embayments and shoreline habitats within Westwater Canyon. Habitat availability within Westwater Canyon was not dependent on the spring peak as much as instantaneous flow. Nursery habitats were basically any low velocity area, whether that be a typical secondary channel backwater or merely a sculpted area in the shoreline bedrock (referred to as embayments). A chi-square analysis of presence/absence YOY chub in Westwater Canyon by habitat depth indicated no selection, supporting the finding of opportunistic habitat use. Habitat depth was positively correlated with peak flows and more strongly correlated with flows at the time of sampling. Shallow habitats were defined as those having a maximum depth < 0.7 m. Much of the available habitat within Westwater Canyon was not formed by sediment deposition as the classic Colorado pikeminnow nursery areas are. Non-native species were found in lower densities in Westwater Canyon than above or below the canyon, again a function of canyon habitat availability. Non-native densities were negatively correlated with the peak flow at the State Line gage.

The analysis of chub recruitment was based on a comparison of cohort (as determined by length frequency analysis) densities (electrofishing CPE) relative from year to year. From this analysis, it appeared the 1994 cohort recruited the best; the 1993 cohort the worst. YOY produced in 1994, although not particularly abundant, had grown larger (45 mm TL by mid-August) than either the 1992 or 1993 cohorts. In addition, overwinter flows for the 1994 YOY cohort were lower and more stable than experienced by the other two cohorts. Survival of all juvenile chubs (> 100 mm TL) appeared to be high, although not quantified.

The humpback chub population in Westwater Canyon was monitored at three sites established for the Interagency Standardized Monitoring Program (ISMP): Miner's Cabin (RK 199.9–198.6), Cougar Bar (RK 194.4–193.6), and Hades bar (RK 192.2–191.8). Densities of adult humpback chub, as referenced by trammel net CPE (fish/23 m net hour), fluctuated greatly from trip to trip but overall remained fairly stable, with the trend in CPE slightly up at Miner's Cabin and slightly down at the other two. The same data for roundtail chub indicated a relatively strong downward trend at all sites. Lincoln-Peterson population estimates, although compromised by large 95% confidence intervals, showed a similar trend in population size for the two species.

Chart, T. E., and L. D. Lentsch. 2000. Reproduction and recruitment of *Gila* spp. and Colorado pikeminnow (*Ptychocheilus lucius*) in the middle Green River 1992–1996. Report C *in* Flaming Gorge Studies: Reproduction and recruitment of *Gila* spp. and Colorado pikeminnow (*Ptychocheilus lucius*) in the middle Green River. Final Report of Utah Division of Wildlife Resources to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 39)

This report presents data collected from five annual monitoring trips in Desolation and Gray (Deso/Gray) canyons of the Green River, Utah; 1992–1996. Pre-project data, in some cases as early as 1985, is incorporated in long term comparisons of catch data. Low velocity habitats were sampled throughout the canyon (two habitats/8 km) with seines. Main channel habitats were sampled with trammel nets, hoop nets, and electrofishing. Main channel sampling occurred at four trend sites (Cedar Ridge - RK 295.7; Surprise Canyon/Rock Creek area - RK 280.5; Joe Hutch - RK 256; and Coal Creek - RK 232.8) each year. Additional sites were sampled each year to determine if Colorado pikeminnow spawned there.

Nonnative cyprinids, most importantly *Cyprinella lutrensis*, dominated the catch in low velocity habitats. Low velocity habitat sampling during August, 1993, resulted in the greatest catch (n = 162) of YOY chubs (approximately 0. 1 fish/m^2). YOY chubs were collected in relatively low numbers every other year of the study. Annual YOY chub CPE was weakly correlated with Green River peak flow (R^2 = 0.1). Back calculated spawning dates indicate chubs spawned in Deso/Gray under a wide range of flows (1,650–25,800 cfs).

Adult and juvenile *Gila* spp. net catch rates at the four monitoring sites remained below 0.2 fish/23 m net-hour throughout this five year period and dropped below 0.1 the final year of study, 1996. Considering pre-project data, adult *Gila* spp. catch rates have been declining since 1989. The 1993 chub cohort was sampled in 1994 as Age 1+ fish and offers the strongest evidence of recruitment since pre-project monitoring in 1989. Juvenile chubs (likely the 1993 and 1994 cohorts) were collected again in 1995. Kolmogorov-Smirnov tests for differing distributions indicated population structure (as characterized in length frequency analysis) of Deso/Gray chubs are dynamic and recently (incorporating 1997 data) were comprised of smaller (younger) individuals.

Colorado pikeminnow trammel net CPE remained low at the four trend sites, with the greatest catch (0.065 and 0.08) collected at RK 280.5 in 1994 and 1995. Concentrations of ripe male pikeminnow were found at Rabbit Valley RK 238) in 1994 and 1995. Concentrations of spawning pikeminnow were also found at Joe Hutch RK 256) in 1997. The Three Fords spawning area was determined to be an 18 km stretch of river between RK 256 and 238, with the focus of spawning shifting within that stretch through time.

Netting catch rates for native catostomids have been in general decline since 1989, however rebounded in recent years. Electrofishing has provided a relatively strong sample of both *Catostomus latipinnis* and *C. discobolus* since 1994 including some strong evidence of recent recruitment. Native catastomid recruitment appears to be more successful since 1993 than was observed in 1992 and during pre-project monitoring years.

Channel catfish (*Ictalurus punctatus*) was the most abundant species collected in main channel habitat each year of study. The only apparent lapse in channel catfish recruitment was observed in 1994 after the higher flows of 1993.

We recommend incorporating Deso/Gray fish community monitoring into the Interagency Monitoring Program and targeting flows of 7,000–8,000 cfs to maximize sampling efficiency. Population estimates at the four trend sampling sites would help validate CPE values collected in this canyon since 1986. If a more intensive study to estimate chub population size is initiated, incorporation of a catfish control component at the trend sites should be considered. This monitoring data set does not lend itself to developing flow recommendations. However, the 1993 cohort of chubs appeared to overwinter better than the 1994 cohort. Overwinter flows averaged 3,250 cfs from Oct 1993–Feb 1994 opposed to 2,250 cfs the next winter.

Chart, T. E., D. P. Svendson, and L. D. Lentsch. 1999. Investigation of potential razorback sucker (*Xyrauchen texanus*) and Colorado pikeminnow (*Ptychocheilus lucius*) spawning in the lower Green River, 1994 and 1995. Final Report of Utah Division of Wildlife Resources to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 38)

In 1994 and 1995, sampling was conducted to determine if razorback sucker and Colorado pikeminnow spawn in the lower 210 km of the Green River. Based on the infrequent collections of adults in the past ten years, sampling efforts for razorback sucker were focused around the mouth of the San Rafael River at Green River kilometer (RK) 156. Investigations of Colorado pikeminnow spawning were centered on a cobble bar at the mouth of Millard Canyon (RK 53.9). Electrofishing and trammel nets were used to sample adults; larval light traps and seines were used to sample the early life stages. One adult razorback sucker was collected while conducting Interagency Standardized Monitoring Program (ISMP) electrofishing in 1995 near Mineral Bottom RK 83.7). This fish (TL = 559 mm, Wt = 2150 g, PIT # = lF74374E68) was caught 69 km below the San Rafael River at RK 86; on 16 May, 1995. No adult razorback suckers were collected as result of specific project efforts near the mouth of the San Rafael River. A total of 48 larval razorback suckers were collected during this study, with the majority (91.7%; n = 44) of those collected in 1994 near the mouth of the San Rafael River. Twenty-eight larvae were collected in the mouth of the San Rafael River and the remaining larvae were collected in habitats immediately downstream. No larvae were collected in habitats upstream of the San Rafael River/Green River confluence. Incorporating the results of this study with those of concurrent efforts in the middle Green River, Muth et al. (1998) determined that larval razorback suckers collected in the lower Green River were likely spawned there. Water temperatures warm earlier each spring in the lower Green River than the middle Green River. The thermal regimes of the Green River at Jensen, Utah, and at Green River, Utah, are discussed in light of razorback sucker spawning time. Further investigation into the timing, magnitude, and specific location of razorback sucker spawning in the lower Green River is recommended. No evidence was found of Colorado pikeminnow spawning in the lower 60 km of the Green River. Based on the results of other project efforts it was determined that the timing of sampling for adults at the Millard Canyon bar was likely better in June, 1994, than in June, 1995. Pikeminnow spawning was delayed throughout the upper Colorado River basin until the latter part of July in 1995. Further investigations into pikeminnow spawning in the lower Green should be more intensive than this effort and should occur within the next five years.

Collins, K. P., and D. K. Shiozawa. 1996. The effects of fish predation on backwater invertebrate communities of the Green River, Utah (Ouray National Wildlife Refuge reach). Final Report of Brigham Young University Department of Zoology to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 12-10).

The potential role of fish predation on the structure of invertebrate communities in backwater habitats of the Green River, a large river in eastern Utah, was examined by placing a series of complete, partial, and no fish exclosures in backwater habitats and sampling benthic and planktonic communities periodically through the summer. The taxa showing the greatest direct treatment effects were the chironomid genus *Tanypus*, the Corixidae, and the planktonic adult copepod. The benthic densities of the naupliar and copepodite stages of copepods showed a negative response to fish exclusion, probably the result of increased levels of Corixidae and *Tanypus,* which are known to prey on benthic organisms. This study indicates that backwater fishes may impact food resources, although invertebrate predation may act in a compensatory manner on certain invertebrate species. This suggests that Colorado squawfish *Ptychocheilus lucius* may undergo resource competition during their post-larval stage. More research is necessary to determine if this is the case.

Converse, Y. K., L. D. Lentsch, and R. A. Valdez. 1999. Evaluation of size-dependent overwinter growth and mortality of age-0 Colorado squawfish. Final Report of Utah Division of Wildlife Resources to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 35)

This report encompasses two important aspects of age-0 Colorado pikeminnow life history. First, we investigated usefulness of scale analysis and length-frequency distributions for evaluating overwinter mortality and growth of age-0 Colorado pikeminnow. Second, we examined associations of age-0 fish length and relative abundance in fall and spring with spatial and temporal degree-day accumulation and flow regimes in the Green River system.

Using the relationship between total number of circuli and total length of young Colorado pikeminnow, we estimated maximum number of circuli formed in the first year for 1) fish that formed a first year growth check and 2) for those that did not. We found that most age-0 Colorado pikeminnow (49%) collected in fall of 1991 (only year scales were collected from age-0 fish) were too small (<40 mm TL) to form a first year growth check but that a first year growth check was present on scales of most adults (75%) collected between 1978–1989.

We then examined length frequency information collected over eight winter seasons (1987 to 1994). In the middle Green River, 45 to 75% of age-0 fish were less than 40 min in fall for years examined (1989 to 1993); in the lower Green River, 50 to 90% of fish were less than 40 min TL in fall for years examined (1987 to 1993). This information suggests that some size dependent mechanism, such as mortality or growth, favored larger Colorado pikeminnow.

To assess size-selective mechanisms (growth or mortality) affecting survival of age-0 Colorado pikeminnow, we examined shifts in length-frequency data, plotted as quantiles, from fall to spring over the 8 year period. In the middle Green River, all years showing a significant effect of a size-selective overwinter mechanism indicated mortality was dominant. In the lower Green River, mortality was dominant in five years, but two years showed dominant size-selective growth. We were not able to discern the interaction between growth and mortality. The relative importance of these size-dependent mechanisms most likely varies from year to year depending on biological and environmental factors like nonnative predation, competition, and degree day accumulation in the first growing season.

These results lead us to explore relationships between physical variables of temperature and flow with size of age-0 Colorado pikeminnow in fall. If degree-day accumulation influenced size of fish in fall, we would have expected to see differences among middle and lower river reaches for both size of age-0 fish entering winter and consequently, their overwinter survival assuming they were hatched during the same period. We calculated degree-day accumulation for pre- and post-dam periods to determine large-scale changes due to Flaming Gorge Dam and then for individual winter and summer seasons that corresponded with fall and spring age-0 fish sampling (1987 to 1994). We found that mean daily water temperatures of the Green River near Jensen, Utah, and near Green River, Utah, were higher on average at the downstream Green River station than the upstream Jensen station, and total degree day accumulation was 37% greater at the downstream station during the period of record. However, no change was found to be associated with dam operations. We also found that degree day accumulation for summer and winter periods was consistently and substantially greater in the lower Green River during the study period. Despite the differences in degree-day accumulation between sites, age-0 Colorado pikeminnow were not larger in the lower Green River in fall.

Furthermore, analysis showed that overwinter degree-day accumulation did not appear to be associated with different size-selective overwinter mechanisms between the middle and lower reaches or among years. One exception to this was a dominant mechanism of size-selective growth occurring only in the lower Green River where temperatures were warmer (1987-88 and 1990-9 1). Fish growth did not appear to be related to mainstem degree-day accumulation which suggests limitations of age-0 Colorado pikeminnow growth may have been due to differences in specific habitat type quantity or quality between the two areas or possibly differential food, predation or competition pressure. This contention is further supported by a lack of a detectable association between age-0 year class size and length in fall and physical flow attributes, such as timing and magnitude of peak flows, average summer flows, and summer degree-day accumulation. A notable but insignificant association between degree-day accumulation and size of age-0 fish in fall in the lower Green river (which did not show up in the middle Green River) suggests limiting factors of early life-stage survival may be different at different sites. In fact, age-1 year class size and length in spring was best predicted by age-0 year class size and length in the fall and was not related to average winter flows or winter degree-day accumulation. The largest and most abundant fall year classes were also the largest and most abundant spring year classes. Such a finding lead us to the conclusion that limiting factors on age-0 Colorado pikeminnow recruitment to age-1 generally occurs before fall of their first year, not overwinter as has been previously hypothesized.

We recommend further investigations between size-dependent overwinter growth and mortality to quantify limitations on age-0 Colorado pikeminnow survival and more information on factors limiting pre-winter recruitment of age-0 Colorado pikeminnow.

Cooper, D. J, and C. Severn. 1994. Wetlands of the Ouray National Wildlife Refuge, Utah: hydrology, water chemistry, vegetation, invertebrate communities, and restoration potential. Final Report of Colorado State University Department of Fishery and Wildlife Biology to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado.

The study area is potentially one of the most valuable floodplain ecosystems in the entire upper Colorado River system. Natural levees occurs adjacent to the river channel and extensive bottomlands occur behind the levees. Bottoms like Wyasket Lake are nearly 1 mile in diameter and provide tremendous floodplain water storage and interaction between the river and floodplain. Nowhere else that we know of in the region does such a wide and potentially active floodplain exist.

Flooding in the study area occurs at Green River flows of approximately 17,000 to 19,000 cfs (481 to 538 m^3/s). Flows of this magnitude historically occurred at a frequency of 1.45 years, with many consecutive years having flooding. Construction of Flaming Gorge Dam has reduced flood frequency to 3.3 years. Thus, long periods of time without flooding occur at present, for example 1987 to 1992. In addition, the establishment of the Ouray National Wildlife Refuge initiated management of large areas for waterfowl, which are not particularly abundant in this region. Their management includes diking the river on the western side of the River. Many bottoms, notable Leota and Sheppard do not flood any more.

Cooper, D. J., and C. Severn. 1994. Wetlands of the Escalante Ranch Area, Utah: hydrology, water chemistry, vegetation, invertebrate communities, and restoration potential. Final Report of Colorado State University Department of Fishery and Wildlife Biology to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado.

Our water chemistry data indicate that there are localized concentrations of selenium, particularly in the northern and southern portions of the study area. The selenium source appears to be shales underlying the terrace east of the wetlands. We hypothesize that the entire northern and southern portions of the study area may contain selenium salts in concentrations that are too high to permit their use as fish restoration sites. However, water samples collected in the central portion of the study area did not contain selenium and with proper management we feel that the site most likely is usable.

Water levels through the winter have not been determined and it is unknown whether fishes trapped in the wetlands over winter, could survive and move back into the river the following spring. Since the wetland water depths are quire shallow we are unsure whether the site freezes to the bottom or not. However, the perennial flows of the escarpment springs would indicate that some oxygenated water does flow into the wetlands and survival may be possible.

We propose a straight forward method for integrating fish into the existing wetlands while preserving the wetland's integrity. This plan is a first step and changes could be made in the future. The plan would allow fishes from the Green River to move into the Escalante wetlands. We propose that one or two high water channels be constructed to allow Green River water to flow from the river into the Escalante wetlands at high and moderate river stages. This connection would occur at river stages above approximately 4,831 to 4,832 feet and would be passive, with water backing in instead of flowing in. Flows required to produce water at this stage occur nearly every year. Since the water would back in from an area adjacent to or downstream from the wetlands, maximum water depth in the wetlands and its duration would be reduced. In addition, sediment deposition in the marsh would be reduced. This channel would introduce fish into the portion of the wetland that contains little selenium and would not require connection of the selenium-free area with the high selenium and high salt groundwater that occurs north of the existing open water bodies.

Water levels in the marshes presently remain high for most of the summer due to groundwater discharge from the terrace escarpment. We expect that under prolonged high flows it could remain high for an even longer period. These high water levels could allow larval fishes introduced to the wetland in May or June to escape back to the Green River in July or even August.

Day, K. S., K. D. Christopherson, and C. Crosby. 1999. An assessment of young-of-the-year Colorado pikeminnow (*Ptychocheilus lucius*) use of backwater habitats in the Green River, Utah. Report B *in* Flaming Gorge Studies: Assessment of Colorado pikeminnow nursery habitat in the Green River. Final Report of Utah Division of Wildlife Resources to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 33)

Colorado pikeminnow nursery habitat characteristics and selection focusing fall sampling for young-of-the-year (YOY) recruitment in backwater habitats were studied in a 16.1 km study reach at Ouray National Wildlife Refuge, Utah, from 1990 to 1996 using Interagency Standardized Monitoring Program (ISMP). The information generated by this study was used for development of a model to predict Colorado pikeminnow use of backwaters based on physical parameters, relationships between spring flows, and nursery habitat formation. This report was generated from the Recovery Implementation Program Scope-of-Work number FG-33. The specific task of this project was to study the Green River within the boundaries of Ouray National Wildlife Refuge to:

1. determine the relationship between quantity of nursery habitats available in the summer period to the number of YOY Colorado pikeminnow present in nursery habitats during the autumn period,

2. describe the relationship between nursery habitat availability and fish habitat selection, and

3. compare intensive sampling and standardized monitoring to assess ways of refining standardized monitoring and ways to make greater use of available data.

A total of 1,043 backwaters and low velocity habitats were sampled three times each year from August 1990 through September 1996 for the presence of endangered fishes. Each backwater sampled was first categorized by physical type; which was determined by its method of formation or current condition. To avoid disturbing the fish, all physical measurements were made after fish communities were sampled with a 3 mm mesh seine. Several statistical analyses were conducted to help interpret significant relationships. Linear regression was performed on four flow parameters peak flow, date of peak flow, flow and duration against backwater numbers, volume and area. Contingency table and X^2 analysis were preformed to test preference for use of habitat classes. The Wilcoxon rank-sum tested the significant differences ($p < 0.05$) of habitat variables between occupied and unoccupied backwaters. Discriminant function analysis was also used to determine if Colorado pikeminnow use of nursery habitats could be predicted by a model of habitat characteristics. Models were developed for each season of each year, for each season for all years, for each year and for all seasons and years pooled. Correlation analysis on catch-per-unit-effort (CPUE) data for all species to show correlation between species CPUE. No consistent trend was found between native ans non-native species.

Findings of this study show that Colorado pikeminnow use large, deep backwaters with high turbidity, and backwaters used by Colorado pikeminnow in the spring were larger and deeper than those used in the summer and fall. Water temperature did not have as much influence on Colorado pikeminnow use of backwaters as expected. Temperature differentials between backwaters and main channel were significant only in the spring. Backwater area and volume available at Ouray NWR was negatively related to peak flows in the preceding spring for all seasons, and no relationship existed between numbers of backwaters available and spring flows. The catch-per-unit-effort of Colorado pikeminnow was positively correlated with bluehead sucker catch, and was not related to spring flows. This was true for most other species captured.

We recommend that periodic high spring flows are needed to rebuild the river channel and re-establish secondary channel backwaters used by Colorado pikeminnow. This rebuilding event should be followed with several years of variable flow aimed at maintaining channel diversity and secondary channel backwaters. Determination of flow events and timing should be based on geologic and hydrologic studies, concurrently being completed. There are two possible modification that should be considered for ISMP young-of-the-year sampling. These include a measure of turbidity and dropping the minimum depth restriction to 0.20–0.25 m. Although not fully addressed here, it is recommended that the final Green River flow regime take into account other species of native fish that show different responses to spring flows and habitats. Variability of the Green River flow regime is likely the best scenario for adequate management of the entire system. Considerable information concerning backwater use by the remaining Green River fish community is still available in this data set, and personnel, time and funding should be dedicated to continue analyses.

Day, K. S., K. D. Christopherson, and C. Crosby. 2000. Backwater use by young-of-year chub (*Gila* spp.) and Colorado pikeminnow (*Ptychocheilus lucius*) in Desolation and Gray Canyons of the Green River, Utah. Report B *in* Flaming Gorge studies: reproduction and recruitment of *Gila* spp. and Colorado pikeminnow (*Ptychocheilus lucius*) in the middle Green River. Final Report of Utah Division of Wildlife Resources to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 39)

Backwater nursery habitat characteristics used by chubs (*Gila* spp.) and Colorado pikeminnow *(Ptychocheilus lucius)* were studied in Desolation and Gray canyons of the Green River, Utah, during 1994 and 1996. This study was conducted as part of the Recovery Implementation Program (RIP) for the Endangered Fish Species in the Upper Colorado River Basin, Scope-of-Work number FG-39. The Flaming Gorge Investigations are a five year program begun in 1992 to provide pertinent information on endangered fishes in the Green River and the effects of flow regulation by the dam. Results of the numerous studies conducted during this period will be used to develop a new Biological Opinion on the future operation of Flaming Gorge Dam. There were a total of ten project objectives, six dealt with biological component and four dealt with geomorphic component. Several of the objectives were handled by more than one research team and the results are reported in more than one final report. Reports are referenced as follows: A-Orchard and Schmidt 1998; B- Day et al. 1999; and C- Chart and Lentsch 1998. The specific tasks of this report were to:

1. determine reproductive success, growth rates, and backwater habitat use of early life stages of *Gila* spp. and Colorado pikeminnow;

2. continue PIT tagging all juvenile and adult *Gila* spp.; and

3. monitor apparent trends in the non-target fish community.

A total 729 backwater and low velocity flow habitats of Desolation and Gray canyons were sampled four times each year between 1994 through 1996 for the presence of endangered fish. Each backwater sampled was first categorized by physical type, and physical measurements were made after fish communities were sampled with a 3 mm mesh seine. Several statistical analyses were conducted to help interpret significant relationships. Linear regression was performed on four flow parameters peak flow, date of peak flow, flow and duration against backwater numbers, volume and area. Contingency table and X^2 analysis were preformed to test preference for use of habitat classes. The Wilcoxon rank-sum tested the significant differences ($p < 0.05$) of habitat variables between occupied and unoccupied backwaters. Discriminant function analysis was also used to determine if Colorado pikeminnow use of nursery habitats could be predicted by a model of habitat characteristics. Models were developed for each season of each year, for each season for all years, for each year and for all seasons and years pooled.

Numbers of backwaters sampled varied between years and seasons. The predominant backwater class was shoreline eddy. Correlations between backwater numbers and flow events could not be rigorously tested because this study represents only three years of flow data. Correlation analyses were run to determine if backwater types were influenced by flow events. Strong negative correlations were seen between the number of migrating sand wave backwaters sampled and annual peak flow and the duration of flow above 50% of the peak, when all sampling periods were included in the analysis. Secondary channel backwaters were negatively associated with duration of flows above 75% of the peak. Although shoreline eddy habitats were not significantly correlated with peak flow events, there was a negative correlation with flows during sampling periods.

Chubs did not show a preference for backwater habitats based on method of formation. Backwaters containing chubs were significantly larger (length, area, depth, volume) and more turbid than unused backwaters, but preferences varied between months. Habitat selection by chubs showed considerable variability. Recent studies from the Grand Canyon indicate that chubs use in-channel shoreline habitats more than backwaters. Other studies show that chubs are often found in main channel habitats and are capable of movement into and through flow. Therefore, this study is likely insufficient for describing characteristics of chub recruitment and nursery habitat use in Desolation and Gray canyons.

Colorado pikeminnow used scour-formed and migrating sandwave backwaters and avoided constricted reach eddies and shoreline eddies. Selection for scour backwaters matched patterns seen in floodplain reaches. Colorado pikeminnow chose larger (length, width, area, volume) backwaters with little cover. Habitat use criteria for this species appeared to be more consistent than for chubs.

Discriminant function analyses could not separate backwaters inhabited by chubs and Colorado pikeminnow from those uninhabited. Discriminant models for Colorado pikeminnow were better than those for chubs, another indication of more definite selection patterns, but they were still not powerful enough for application.

All sampled habitats were overwhelmingly dominated by nonnative species. Catch-per-unit-effort for a few of these species was positively correlated with chubs and Colorado pikeminnow. Flow regulation alone may not be adequate for control of nonnative fish.

It is recommended that additional studies be conducted on chub nursery habitat use. Additional studies should be conducted on effects of spring discharge, single year and multiple year interaction, on chubs and Colorado pikeminnow. Habitat associations and flow/recruitment relationships for non-listed native fishes should be analyzed. Nonnative fish recruitment and habitat use, as well as interactions with native fishes should be pursued.

FLO Engineering, Inc. 1996. Green River flooded bottomlands investigation, Ouray Wildlife Refuge and Canyonlands National Park, Utah. Final Report of FLO Engineering, Inc. to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. ***Abstract excerpted from Executive Summary***

Two study reaches were selected for the investigation of bottomlands flooding and backwater inundation in the Green River. The first reach was located in the vicinity of Ouray National Wildlife Refuge, near Vernal, Utah, and the second reach was located in Canyonlands National Park near Anderson Bottom. At Ouray, the frequently flooded bottomlands were the subject of the investigation. In Canyonlands, the focus of the investigation was the backwaters created by side canyon channels during high river flows. Hydrographic data was collected at the two sites during the 1995 high flow season. An analysis of U.S. Geological Survey stream gaging data for the period of record at the Green River gages at Jensen and Green River, Utah, and simulation of flood levels using the Corps of Engineers HEC-2 water surface profile model were also completed.

The results of the Ouray inundation analysis indicate that overbank flooding is initiated at discharges ranging from 15,800 to 22,700 ft^3/s (447 to 643 m^3/s) under existing conditions with levees. If levees were removed, inundation may be initiated at most locations with discharges of approximately 18,600 ft^3/s (526 m^3/s). This discharge corresponds to a return period of 2.6 years and an average annual duration of 4.4 days. Similarly, if 2 to 3 foot deep side channels were excavated at appropriate locations to connect the bottomlands to the river, flooding could be initiated at all Ouray bottomlands with a discharge of 13,000 ft^3/s (368 m^3/s). The 13,000 ft^3/s discharge has a return period of 1.5 years and an average annual duration of 11 days. Through a combination of levee removal, side channel excavation and application flooding, it would be practical to flood over 2,185 hectares at discharges on the order of the 1.5-year return period. This would correspond to significant flooding every two out of three years on the average and would provide flooding frequency and duration similar to pre-1963 conditions. The maximum possible area of inundation is about 4,050 hectares, which currently occurs for a discharge over 37,000 ft^3/s (1,047 m^3/s) (100-year event).

In Canyonlands, flooding of the side canyon backwater areas initiates at a discharge of approximately 7,000 ft^3/s (198 m^3/s, and increases linearly up to bankfull discharge, 39,000 ft^3/s (1,104 m^3/s). It was estimated that 200 hectares of floodplain became inundated between 30,000 ft^3/s (849 m^3/s) (5-year) and 53,000 ft^3/s (1,500 m^3/s) (100-year).

Restoration of flooded bottomlands habitat at Ouray could be accomplished through a combination of increased water surface elevations, prolonged peak flow duration, lower bank or levee heights and constructed inlets. Construction activities to restore flooding must address channel stability issues, potential increase in flood levels, sediment deposition, and potential changes in channel morphology.

In Canyonlands, enhancing the flooding of side canyon backwater areas can be accomplished only through flow augmentation. It is not practical to restore or enhance flooding through physical alteration of the backwater habitat areas. Because of the magnitude of the required overbank flow, flow augmentation is probably impractical as well.

FLO Engineering, Inc. 1997. Green River discharge monitoring. Final Report of FLO Engineering, Inc. to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 72) ***Abstract excerpted from results and conclusions***

The results available for the 1996 monitoring of the Green River runoff indicate several key findings regarding flow routing. First, for flows in the range of 12,000 to 18,000 ft^3/s (340 to 509 m^3/s), the travel time from Jensen to Stillwater Canyon is approximately 85 hours and the mean velocity is about 1.1 m/s. Second, for flows from 5,000 to 12,000 ft^3/s (142 to 340 m^3/s), the travel time between the same two points is approximately 100 hours with a mean velocity of 0.9 m/s. Third, downstream from Jensen, the Green River is a gaining river, that is, average discharge increases with distance downstream from Jensen. Fourth, the sharp peak discharge at Jensen flattens and increases in duration with the inflows from the White and Duchesne Rivers.

FLO Engineering, Inc. 1997. Green River floodplain habitat restoration investigation – Bureau of Land Management Sites and Ouray National Wildlife Sites near Vernal, Utah. Final Report of FLO Engineering, Inc. to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. ***Abstract excerpted from Executive Summary***

Ten Green River study reaches containing bottomlands were selected for floodability assessment. The ten bottomland areas were located near Vernal, Utah, stretching over 40 river kilometers. Five of the ten sites were located on Bureau of Land Management (BLM) sites and the other five sites were located on the Ouray National Wildlife Refuge (ONWR). The objectives of the study were to determine: (1) the discharge at which each of the bottomlands flood; (2) areas of inundation for each bottomland for different flood levels; and (3) levee removal (natural or artificial) strategies in order to flood the bottomlands at a more historical frequency and magnitude.

The BLM sites are characterized by high, heavily vegetated natural levees. The BLM bottomland sites partially fill and drain on an annual basis through seepage connections as the river rises during the runoff season. Restoration alternatives have been proposed for these sites to allow flooding to occur at 13,000 ft^3/s (368 m^3/s), a discharge with a return period of 1.5 years based on post-1963 hydrology. About 57 hectares of flooded bottomland habitat would be available at these sites.

For the ONWR bottomland sites, more acreage is available for flooding than at the BLM sites. About 258 hectares could be flooded at 13,000 ft^3/s with selective levee removal. Fish passage to these bottomlands would be available at close to assumed historic frequency and duration.

Grams, P. E., and J. C. Schmidt. In press. Geomorphology of the Green River in the eastern Uinta Mountains, Colorado and Utah. *In* A. J. Miller, editor. Varieties of fluvial form. John Wiley and Sons, New York.

Longitudinal profile, channel cross-section geometry, and depositional patterns of the Green River in its course through the eastern Uinta Mountains are each strongly influenced by river-level geology and tributary sediment delivery processes. We surveyed channel cross-sections at 1-km intervals, mapped surficial geology, and measured size and characteristics of bed material in order to evaluate the geomorphic organization of the 70-km study reach. Canyon reaches that are of high gradient and narrow channel geometry are correlated with the most resistant lithologies exposed at river level and the most frequent occurrences of tributary debris fans. Meandering reaches that are characterized by low gradient and wide channel geometry are correlated with river-level lithology that is of moderate to low resistance and very low debris fan frequency. The channel is in contact with bedrock or talus along only 42% of the bank length in canyon reaches and there is an alluvial fill of at least 12 m that separates the channel bed from bedrock at 3 borehole sites. Thus the influence of lithology on channel form is indirect. The influence of lithology primarily operates through the presence of resistant boulders in debris fans that are delivered by debris flow from steep tributaries. Shear stress estimates indicate that bed material size and channel form and steepness are in approximate adjustment for discharges of about the 10-year recurrence flood as determined for unregulated streamflow. Downstream transport of gravel is limited; gravel-bar lithology shows a strong relationship to the source lithology of the adjacent upstream debris fan. These observations suggest that the Green River through the eastern Uinta Mountains has been dominated by aggradation during recent geologic time.

The depositional settings created by debris fans consist of (1) channel-margin deposits in the backwater above the debris fan, (2) eddy bars in the zone of recirculating flow below the constriction, and (3) expansion gravel bars in the expansion below the zone of recirculating flow. These fan-eddy complexes are the storage location of about 70%, by area, of all fine- and coarse-gained alluvium contained within the canyons above the low-water stage. Immediately adjacent meandering reaches contain an order of magnitude more alluvium by area but have no debris fan-created depositional settings.

Guensch, G. R., and J. C. Schmidt. 1996. Channel response to high discharges in 1996, Green River at Ouray and Mineral Bottom. Annual Progress Report of Utah State University Department of Geography and Earth Resources to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado.

The channel response of the Green River to the 1996 flood was measured in areas considered to contain critical Colorado squawfish nursery habitat. These areas are located at Ouray and Mineral Bottom. Cross sections at each of these study reaches were surveyed during various flood stages in 1996. Each reach was also topographically mapped. Cross sections surveyed in 1996 were compared with surveys from 1993 and 1994. At Ouray, the 1996 flood created higher elevation sand bars than existed after the 1993 or 1994 floods. Bar building occurs during flood recession. At Mineral Bottom, bars do not build nearly as high, relative to the peak flood stage, as they do at Ouray. As a result, less nursery habitat is available at Mineral Bottom than at Ouray. Our data illuminate several characteristics of the Mineral Bottom study reach that may explain its geomorphic behavior. The channel at Mineral Bottom is generally narrower than at Ouray, has a slightly higher gradient, and is more isolated from its historic floodplain due to its high banks. The topographic maps show that bar complexity at Ouray in 1996 was less than in 1994 or 1995, but greater than that following the 1993 flood of slightly less magnitude.

Gutermuth, F. B., L. D. Lentsch, and K. R. Bestgen. 1994. Collection of age-0 razorback suckers (*Xyrauchen texanus*) in the lower Green River, Utah. Southwestern Naturalist 39:389–391. ***Abstract excerpted from results and conclusions***

On 30 July 1991, two early juvenile razorback suckers (*Xyrauchen texanus*; 36.6 and 39.3 mm total length) were collected from a backwater on the lower Green River, Utah, near Hell Roaring Canyon (89.5 km upstream of the confluence with the Colorado River). This is this first verified evidence of razorback sucker survival beyond the larval period in the upper Colorado River basin since that reported in 1965. The specimens were captured at 1325 hours by seine from a silt-bottom backwater 3.5 m wide and 24.5 m long, opening to 12 m at the mouth. Slightly turbid water and a large boulder were the only cover. Maximum water depth was 0.7 m, but depth at point of capture was 0.1 to 0.2 m. Surface water temperature was 34ºC. Other fishes collected included nonnative common carp (*Cyprinus carpio*), red shiner (*Cyprinella lutrensis*), sand shiner (*Notropis stramineus*), fathead minnow (*Pimephales promelas*), channel catfish (*Ictalurus punctatus*), and green sunfish (*Lepomis cyanellus*). Probable hatching dates for the two juvenile razorback suckers, based on otolith-aging, were 3 and 7 June.

Haines, G. B. 1995. Effects of temperature on hatching success and growth of razorback sucker and flannelmouth sucker. Final Report of U.S. Fish and Wildlife, Vernal, Utah, to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 5e) ***Abstract excerpted from results and conclusions***

Laboratory experiments were conducted to assess the effects of water temperature on the developmental rate and hatching success of embryos and growth of larvae of the endangered razorback sucker (*Xyrauchen texanus*) and the sympatric and common flannelmouth sucker (*Catostomus latipinnis*). Embryos and larvae were reared at 12, 16, or 20ºC for 45 d post-fertilization. Mean number of days between fertilization and peak hatching of embryos decreased as water temperature increased for both species; 6.5 d (20ºC) to 12.5 d (12ºC) for razorback sucker and 6.0 d (20ºC) to 16.5 d (12ºC) for flannelmouth sucker. The period from first to last hatch averaged 2.0 d longer for razorback sucker than flannelmouth sucker over all temperatures. Percent hatch of flannelmouth sucker embryos was independent of water temperature and, at each water temperature, was higher for flannelmouth sucker (83–91%) than for razorback sucker (48–67%); hatching success of razorback sucker embryos increased as water temperature increased. At 20ºC on each sampling day, embryos and larvae of flannelmouth sucker were substantially larger than those of razorback sucker.

Haines, G. B., D. W. Beyers, and T. Modde. 1998. Estimation of winter survival, movement and dispersal of young Colorado squawfish in the Green River, Utah. Final Report of U.S. Fish and Wildlife Service, Vernal, Utah, to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 36)

Population estimates for age-0 and age-1 Colorado squawfish in two 32-km reaches of the Green River were made using capture-recapture procedures. Comparisons of autumn and spring population estimates were used to assess overwinter survival and evaluate factors that affect it. Previous research using traditional methodology has demonstrated that estimates obtained using catch per unit effort (CPUE) are unreliable for assessing overwinter survival. Capture-recapture provides a more rigorous basis for estimating abundance of young Colorado squawfish because it can account for variable capture probabilities.

Objectives of this study were to employ capture-recapture methods to (1) compare estimates of abundance from capture-recapture and CPUE methods; (2) estimate overwinter survival of age-0 Colorado squawfish; (3) estimate seining catchability coefficients for autumn and spring sampling; (4) determine extent of downstream movement of marked Colorado squawfish between 1 November and 1 April; and (5) determine the effect of timing and magnitude of spring flows on dispersal of age-1 Colorado squawfish.

We found little evidence that abundance estimates from CPUE accurately reflect the number of young Colorado squawfish in study reaches in the Green River. There was only a weak correlation ® = 0.30, $P = 0.47$) between estimates of abundance from CPUE and capture-recapture. On several occasions, CPUE estimates had precision that was comparable to that achieved with capture-recapture, but the estimates differed by as much as 217%. Inaccuracy and greater variability of CPUE was attributed to effects of water temperature on capture probability. Evidence suggests that young Colorado squawfish are less likely to be caught when water temperatures are cool, regardless of their abundance.

Overwinter survival probabilities of age-0 fish ranged from 0.06 to 0.62. Three of four estimates were similar and ranged from 0.56 to 0.62. Low overwinter survival (0.06) during 1995-1996 may have been due to small size of age-0 fish in autumn or relatively high winter discharge.

Recaptures of marked age-0 and age-l Colorado squawfish showed that they moved less than 16 km downstream during sampling periods that ranged from 2 to 21 days Similarly, age-0 fish that were marked in autumn and recaptured the following spring moved less than 16 km downstream after being at large for 170 to 200 d. The role of spring flooding in redistribution of age-1 Colorado squawfish remains unclear because few fish were captured during post-runoff surveys conducted in July and August.

Hamilton, S. J., and B. Waddell. 1994. Selenium in eggs and milt of razorback sucker (*Xyrauchen texanus*) in the middle Green River, Utah. Archives of Environmental Contamination and Toxicology 27:195–201.

Eggs from three females and milt from five male endangered razorback suckers (*Xyrauchen texanus*) were collected from the Razorback Bar (about 20 km upstream of Ashley Creek) in the Green River of northeastern Utah. Eggs, but not milt, had concentrations of selenium that were above the range of selenium concentrations in control fish from laboratory studies or reference fish from field studies. The concentrations, however, were below those reported in selenium-exposed fish that had reproductive problems in laboratory studies or field investigations. Tests with three streamside spawned pairs of razorback suckers, which were sampled for eggs and milt in this study, resulted in no hatching of fertilized eggs. Concentrations of selenium in eggs and milt were significantly correlated with selenium concentrations in muscle plugs taken from the same fish, but egg and milt concentrations were not significantly different from muscle plugs. Selenium concentrations in eggs of razorback suckers in the Green River may be sufficiently elevated to cause reproductive problems that are contributing to the decline of this species in the upper Colorado River basin.

Hamilton, S. J., R. T. Muth, B. Waddell, and T. W. May. 1998. Selenium and other trace elements in wild larval razorback suckers from the Green River, Utah. Final Report of U.S. Geological Survey Environmental and Contaminants Research Center to U.S. Bureau of Reclamation Irrigation Drainage Program, Denver, Colorado.

Contaminant investigations of the middle Green River, Utah, have documented selenium contamination at sites receiving irrigation drainage. The middle Green River provides critical habitat for four endangered fishes including the largest extant riverine population of razorback sucker (*Xyrauchen texanus*). Although 2,175 larval razorback suckers were collected from the river between 1992 and 1996, very few juveniles have been captured within recent decades. Selenium concentrations were measured in larval razorback suckers collected from five sites in the middle Green River to assess the potential for adverse effects on recruitment of larvae to the juvenile stage and the adult population. Larvae from all sites contained selenium concentrations at or above the proposed toxic threshold of 4 Fg/g for adverse biological effects in fish, derived from several laboratory and field studies with a wide range of fish species. At two sites, Cliff Creek and Stewart Lake Drain, selenium concentrations in larvae increased over time as fish grew, whereas selenium concentrations decreased as fish grew at Sportsman's Drain. Evaluation of a 279-larvae composite analyzed for 61 elements demonstrated that selenium, and to lesser extent vanadium, were elevated to concentrations reported to be toxic to a wide range of fish species. Elevated selenium concentrations in larval razorback suckers from the five sites suggests that selenium contamination may be widespread in the middle Green River, and that survival and recruitment of larvae to the juvenile stage may be limited due to adverse biological effects. Selenium contamination may be adversely affecting the reproductive success of endangered razorback sucker.

Harvey, M. D., R. A. Mussetter, and E. J. Wick. 1993. A physical process-biological response model for spawning habitat formation for the endangered Colorado squawfish. Rivers 4:114–131.

A three-level, physical process-biological response model for spawning habitat formation was developed from field measurements, hydraulic modeling (HEC-2), and analysis of a known spawning bar at River Mile (RM) 16.5 in the Yampa River. Sediment deposition and bar formation occur at discharges greater than 10,000 ft^3/s (283 m^3/s), a discharge at which downstream hydraulic controls cause backwater and reduced transport capacity of the flows. Spawning habitat is formed by bar dissection and erosion at a range of flows between 400 and 5,000 ft^3/s (11 to 142 m^3/s) when the local hydraulic energy is greatest because of reduced tailwater downstream, and sediment delivery tot he chute channels is reduced by deposition in an upstream pool. The process-response model appears to be validated by fish-capture data at this, and another spawning bar at RM 18.5, on the Yampa River during both the 1991 and 1992 runoff seasons.

Harvey, M. D., and R. A. Mussetter. 1994. Green River endangered species habitat investigations. Resource Consultants & Engineers, Fort Collins, Colorado. RCE Ref. No. 93-166.02.

This investigation of a known Colorado squawfish spawning bar located at the head of Gray Canyon on the Green River tested the researchers' proposed physical process-biological response model (PRM) for spawning habitat formation. This model was initially developed from data and analyses conducted about 27 km upstream from the Yampa and Green Rivers confluence in the lower Yampa River Canyon (Harvey et al., 1993). The PRM indicates that high discharges are responsible for the construction of the spawning bar, but not the actual formation of the spawning habitat. Downstream hydraulic controls cause a backwater condition that results in the formation of the bar as a heterogeneous mass of sediments are deposited. Reduced tailwater during recessional flows causes a steepening of the local hydraulic gradient, which in turn leads to bar dissection and erosion of chute channels. Dissection of the bar causes the fines to be flushed and this is enhanced by reduced sediment delivery from upstream due to deposition in the upstream pool. A clean cobble substrate, with the constituent cobbles at incipient motion, and suitable for egg adhesion, is formed in the subaqueous tertiary bars that are located within the chute channels.

The downstream hydraulic control for the spawning bar is formed by two coarse grained and horizontally opposed alluvial fans that have prograded into the channel to form a constriction in a relatively wide valley segment of the Green River. Hydraulic analysis of the reach indicated that two of the three midchannel bars located in the middle and left branch channels meet the PRM criteria for squawfish spawning habitat; gravels and cobbles that constitute the midchannel bars attain a condition of incipient motion, and therefore, meet a criterion of the PRM.

In common with other rivers draining the Colorado Plateau (Webb and others, 1988), the vast majority of rapids (95%), and hence channel constrictions, are the result of tributary alluvial fans that prograde out into the channel. Although the identified site meets PRM criteria it should be recognized that other factors may also be involved in determining spawning habitat.

Available data do not indicate that construction of Flaming Gorge Reservoir has caused a reduction in the alluvial fan constriction ratios at this site. The peak flow record immediately before and after construction of Flaming Gorge Reservoir has been very similar.

Hayse, J. W., S. F. Daly, S. F, A. Tuthill, R. Valdez, B. Cowdell, and G. Burton. 2000. Effect of daily fluctuations from Flaming Gorge Dam on formation of ice covers on the Green River. Final Report of Argonne National Laboratory and the U.S. Army Cold Regions Research and Engineering Laboratory to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 83)

This report provides results and conclusions of a detailed investigation of ice processes in the main channel of the reach of the Green River between the downstream end of Split Mountain (RM 320) and the Ouray, Utah Bridge (RM 248). The objective of the study was to examine the influence of daily fluctuations in water releases from Flaming Gorge Dam on river ice processes in this reach, which serves as an overwintering area for endangered Colorado pikeminnow and razorback sucker. The objective of the study was met through examination of historical records of winter water and air temperatures, flow measurements, and ice observations; through measurements of differences in ice conditions under steady and fluctuating flow regimes; and through calibration and use of an ice process model to compare hydraulic and ice conditions expected under steady and fluctuating flow regimes.

Examination of historic measurements of water and air temperatures, and historic and current (winter of 1996-1997) ice observations indicated that ice occurred within the Green River study reach during every winter for which reliable observations were available. Historic observations of ice recorded by the USGS during discharge measurements were determined to be unreliable indicators of the duration of ice presence during past winters because of the intermittent nature of the observations.

Measurements of ice thickness were made at 17 cross-section locations within the study reach during the winter of 1996-1997 under steady flows and after several days of fluctuating flows resulting from initiation of a peaking flow regime at Flaming Gorge Dam. Ice cover broke up at the three upstream-most cross section locations in the study reach during the first few days of fluctuating flows. These three sites were located upstream of the Jensen Bridge, at RM 307.0, 308.2,and 316.3. Mean ice thickness at the 14 remaining cross section locations (between Jensen Bridge [RM 300] and Ouray Bridge [RM 248]) was not significantly different under steady flows and fluctuating flows.

A change in flow of approximately 1,800 cfs at the Jensen gage resulted in measured stage (surface elevation) changes at seven sample locations that ranged from 24 cm at the upstream end of the study reach to 6 cm at the downstream end of the study reach. The upstream 5 miles of ice cover in the study reach broke up after several days of fluctuating flows.

Formation of ice cover in the study reach appeared to follow a consistent pattern during winters for which historical observations were available and the daily release schedule of Flaming Gorge Dam, whether steady or fluctuating as a result of hydropower demand, was found to have no apparent effect on the basic pattern. The initial type of ice reported for each winter for which historic observations were available was frazil ice, transported at the water surface in the form of slush, floes, and pancake ice. A stationary ice cover formed initially near the Ouray Bridge and progressed upstream from that point. Ice cover in all years is probably formed primarily by juxtaposition of floes up to about RM 290. Upstream of RM 290, underturning of ice floes and a rougher ice surface were more typical during the 1996-1997 study and is probably similar under most winter conditions. The reported upstream extent of the ice cover was typically at least up to RM 302 and often extended upstream of this point. No complete ice cover was reported upstream of Chew Bridge (RM 316), except for short, isolated stretches during a particularly severe winter. Apparently the river gradient in the study reach is too steep to allow ice progression past this point during most winters.

A numeric model of dynamic ice formation in the Green River was developed using empirical information and used to simulate ice cover formation on the Green River for the winters of 1989-90 through 1995-96. The ice model results were in general agreement with historical ice observations during these years. Analysis of hydraulic conditions that occurred during the winter of 1996-1997, together with the ice process model was used to evaluate the potential effects of daily fluctuations on ice formation and breakup. The results indicated that daily fluctuations of releases similar to those observed during 1996-1997 (approximately 1,800 cfs) from Flaming Gorge Dam would be unlikely to affect ice cover in the main channel of the Green River downstream of RM 300 (Jensen Bridge) under most winter conditions. Upstream of the Jensen Bridge daily fluctuations have a more pronounced effect and are more likely to affect ice cover formation and breakup. During especially cold winters, when production of frazil ice would be high, large daily fluctuations in flow would probably transport frazil ice beneath the ice cover in the reach above the Jensen Bridge. This would result in an ice cover thicker than ice covers that would occur through this reach under steady flow. Frazil depositions several feet thick were observed in this reach during the winter of 1987-1988 when water releases from Flaming Gorge Dam fluctuated daily. The ice cover that developed in this reach under conditions of steady flow during the 1997 field survey was about 0.8 feet thick. Recommendations resulting from this study include:

1. To reduce the transport and deposition of frazil ice beneath ice covers in main channel areas used by overwintering endangered fishes, develop winter operations of Flaming

Gorge Dam that take frazil production and the upstream extent of the ice cover into account.

2. Initiate a program to collect accurate hourly or sub-daily water temperatures during winter to allow for more accurate temperature modeling for the Green River and to investigate the effect of release volumes and fluctuating flows on temperature regimes in downstream areas of the Green River.

3. Conduct additional investigations to characterize winter conditions in backwaters and other low-velocity habitats that may serve as overwintering areas for juvenile endangered fishes.

Mabey, L. W., and D. K. Shiozawa. 1993. Planktonic and benthic microcrustaceans from floodplain and river habitats of the Ouray Refuge on the Green River, Utah. Department of Zoology, Brigham Young University, Provo, Utah.

This study compares microcrustacean densities and species occurrence of benthic and planktonic copepods and cladocerans in backwater, river channel, and floodplain habitats of the Green River, Utah. Samples were taken during the summer of 1991. Samples were taken using a 1.27-cm diameter benthic core sampler and vertical plankton tows with a 63-micron plankton net. In all, 28 species were collected. The copepods are represented by six species of cyclopoids, six species of calanoids, and two species of harpacticoids. Fourteen species of cladocerans were collected. The highest densities were found in the floodplain. Benthic densities ranged from 4,896–23,059/m^2 in backwater habitats, 948–6,138/m^2 in river habitats, and 85,812–262,808/m^2 in floodplain habitats. Plankton densities ranged from 1,450–63,353/m^3 in backwaters, 317–1,312/m^3 in the river, and 205,923–690,187/m^3 in the floodplain. A comparison of the first sample periods for the floodplain (June), the Ouray backwater (July), and river sites (July) indicate that the density of the benthos was 41 times greater in the floodplain than in the other habitats, and the plankton density in the floodplain was 29 times greater than the backwater and 157 times greater than the river.

Modde, T. 1996. Juvenile razorback sucker (*Xyrauchen texanus*) in a managed wetland adjacent to the Green River. Great Basin Naturalist 56:375–376 (Recovery Program Project CAP-6) ***Abstract excerpted from results and conclusions***

The largest reproducing riverine population of endangered razorback sucker (*Xyrauchen texanus*) is in the middle Green River, Utah and Colorado, but recruitment is limited and few juveniles have been collected recently. This note reports the capture of juvenile and adult razorback suckers in 1995 from Old Charlie Wash, a 60-ha managed wetland adjacent to the middle Green River on the Ouray National Wildlife Refuge, Utah. Spring flows of the Green River in 1995 peaked at about 595 m^3/s and inundated Old Charlie Wash between 23 May and 1 July; inundation was at flows greater than 481 m^3/s. When runoff subsided, no additional water was added and fish in the wetland were isolated from the river. Fish collections in the wetland were made weekly from 23 May to 1 July and every 2 weeks from 2 July to 31 August. The wetland was drained from 25 September to 12 October, and fishes were collected from the outlet every other day during the first 2 weeks and daily (expect for 9 October) during the 3rd week. Twenty-eight juvenile razorback suckers were collected during draining. Sizes of the juvenile razorback suckers ranged from 74–125 mm total length (mean, 94 mm TL) and mass ranged from 3–18 g (mean, 9.5 g). Eight adult razorback suckers (461–525 mm TL and 1034–1650 g) were also captured; six prior to and two during draining. It is unknown whether the juvenile razorback suckers originated from riverine spawning or were produced in Old Charlie Wash. However, their occurrence supports speculation that floodplain wetlands may be important razorback sucker nursery habitats.

Modde, T. 1997. Fish use of Old Charlie Wash: an assessment of floodplain wetland importance to razorback sucker management and recovery. Final Report of U.S. Fish and Wildlife Service, Vernal, Utah, to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project CAP-6) ***Abstract excerpted from Executive Summary***

This study was conducted in Old Charlie Wash, a managed wetland adjacent to the middle Green River on the Ouray National Wildlife Refuge at river kilometer 402. Objectives were to (1) determine if adequate water-quality conditions and prey (i.e., zooplankton) densities existed in the wetland to support age-0 razorback suckers through the summer months, (2) describe the composition, temporal occurrence, and habitat use of fishes in the wetland, and (3) integrate information from this study with existing knowledge to recommend management actions that will enhance recovery of razorback sucker. The goal was to determine whether floodplain wetlands are used by age-0 razorback suckers, and if so, propose strategies to manage these habitats for recovery of this species.

During the high-water years (1995 and 1996) of this study, favorable zooplankton densities, water temperatures, water quality, water depth, and cover existed in floodplain depressions to support age-0 razorback suckers and other fishes. Conversely, main-channel habitats were not as conducive as rearing sites for larval razorback suckers due to lower water temperatures, less food, and limited cover. During spring runoff in 1995 and particularly 1996, most larval razorback suckers were found in the Green River after floodplains were isolated from the main channel. Thus, although favorable nursery sites were located off-channel, connectivity between the river and floodplain did not last long enough for all razorback sucker larvae to access these areas. Maintaining connectivity of the floodplain to the river via levee removal and flood-flow duration will increase access and use of favorable nursery habitats by larval razorback suckers in the middle Green River.

Old Charlie Wash continued to provide favorable rearing sites for age-0 native and nonnative fishes in the summer months of 1995 and 1996. In two successive high-flow years, wild razorback sucker larvae survived and grew in the floodplain wetland, which was dominated by nonnative predators and competitors. If the number of razorback sucker juveniles caught in Old

Charlie Wash each year (28 in 1995 and 45 in 1996) was extrapolated to the area of available depression wetlands in the middle Green River, a minimum of 363 and 582 wild, acclimated age-0 fish 100–125+ mm long would have been produced in the middle Green River in 1995 and 1996, respectively. Because flows in the Green River were historically of greater magnitude and nonnative fishes were not present, razorback suckers may have been able to recruit in both depression and terrace wetlands. However, under the current reduced flow conditions, and dominance of nonnative fishes in both main-channel and floodplain habitats, depression floodplains offer the greatest probability for rearing age-0 razorback suckers. In this regard, the availability of floodplain wetlands to razorback suckers could be a primary factor in recovery of the species.

Modde, T., K. P. Burnham, and E. J. Wick. 1996. Population status of the razorback sucker in the middle Green River. Conservation Biology 10:110–119.

The razorback sucker, *Xyrauchen texanus*, in the middle Green River (U.S.A.) has been described as a static population consisting of old individuals that will eventually disappear through attrition. Capture data between 1980 and 1992 indicated a constant length frequency despite a slow but positive growth rate of individual fish. Abundance and survival estimates indicated that the population of razorback sucker in the middle Green River is precariously low but dynamic. Although high variation existed among survival estimates, no significant decrease in the population between 1982 and 1992 could be detected. The low level of recruitment occurring in the razorback sucker population of the middle Green River was related to high-flow years, indicating that floodplain habitats may be necessary for survival of the species.

Modde, T., and E. J. Wick. 1997. Investigations of razorback sucker distribution, movements and habitats used during spring in the Green River, Utah. Final Report of U.S. Fish and Wildlife Service, Vernal, Utah, to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 49) ***Abstract excerpted from Executive Summary***

This report presents information on movements and, to a limited extent, habitat use by adult and juvenile razorback sucker *Xyrauchen texanus* as well as a comparison of growth and survival of juvenile razorback sucker between main-channel and off-channel habitat. Habitat availability information is limited to the identification of flows necessary to inundate Old Charlie Wash (RK 402), a floodplain wetland on the Ouray National Wildlife Refuge. The objectives of this project were to 1) describe movement and habitat use patterns of adult razorback sucker, 2) describe the growth and survival of immature razorback sucker in wetlands relative to main channel habitat, and 3) determine flows required to inundate Old Charlie Wash.

Capture data during 16 years (1975,1978–1992) and radio-telemetry data during three successive spawning events (1993–1995) were used to describe seasonal and spawning movements of adult razorback sucker in the middle Green River. Greatest distance traveled by razorback sucker occurred just prior to and shortly after spawning. Movement to spawning sites was associated primarily with discharge, with the greatest numbers present on the spawning bar prior to peak flow. Although data suggested that many razorback sucker in the middle Green River spawned at a single location between river kilometers 492 and 501, other spawning sites were also used. Use of multiple spawning sites by several fish suggested a single reproductive population in the middle Green River.

Experimental studies to evaluate growth and survival of captive larval and juvenile razorback sucker in wetland habitat provided limited useful information. Growth and survival of juvenile razorback sucker in wetlands, with the exception of Old Charlie Wash, tend to be higher than in main channel backwater habitat. An experiment on growth and survival of larval and juvenile razorback sucker in the presence of red shiner *Cyprinella lutrensis* was unsuccessful because all razorback sucker larvae were consumed by red shiner and only one razorback sucker juvenile survived to the end of the experiment. Predation of larval razorback sucker by adult red shiner suggests the potential for nonnative impacts on the survival of endangered fishes in wetlands.

An evaluation of availability of habitat in the spring was limited to defining river flows necessary to connect Old Charlie Wash (between 405 m^3/s and 455 m^3/s), an 80 ha wetland on the Ouray National Wildlife Refuge, with the Green River.

Modde, T., and D. B. Irving. 1998. Use of multiple spawning sites and seasonal movement by razorback sucker in the middle Green River, Utah. North American Journal of Fisheries Management 18:318–326. (Recovery Program Project 49)

Radiotelemetry data through three successive spawning events (1993–1995) and capture data for 15 years (1975, 1979–1993) were used to describe movement patterns and fidelity to spawning sites by male razorback suckers *Xyrauchen texanus* in the middle Green River, Utah. Movement to spawning areas was influenced primarily by discharge. The longer distances traveled by male razorback suckers were in a downstream direction and occurred just before and shortly after spawning. Three of six surviving males implanted with radio transmitters were located on more than one spawning site between 1993 and 1995. Thus, although most razorback suckers in the middle Green River spawned in a single area between river kilometers 492 and 501 (from the confluence of the Green and the Colorado rivers), other spawning areas were probably used. Tag recapture and telemetry data supported the hypothesis that razorback suckers in the middle Green River represent a single reproductive population.

Muth, R. T., and S. M. Meismer. 1995. Marking otoliths of razorback sucker embryos and larvae with fluorescent chemicals. Southwestern Naturalist 40:241–244. (Recovery Program Project 12-9) ***Abstract excerpted from results and conclusions***

Laboratory experiments were conducted to determine optimum treatments of alizarin complexone (ALC) or tetracycline hydrochloride (TC) for marking otoliths in late embryos or recently hatched larvae of razorback sucker (*Xyrauchen texanus*) through immersion in solutions of these chemicals. Once deposited in bone, ALC fluoresces red and TC fluoresces yellow when illuminated by ultraviolet light. Fish survival and mark quality were evaluated in different ALC or TC concentrations and immersion durations for (1) single treatment of embryos with either chemical, producing single marks and (2) single treatment of larvae with each chemical, producing double marks. Otoliths from all larvae in the single-mark or double-mark experiments had fluorescent marks. Embryo and larval survival decreased and mark quality increased as chemical concentrations and immersion durations increased. For best fish survival and mark quality, recommended ALC treatments are 12 to 30 h in 150 to 350 mg/L for embryos and 6 to 18 h in 12.5 to 50 mg/L for larvae. Recommended TC treatments are 18 to 30 h in 150 to 350 mg/L for embryos and 6 to 18 h in 150 to 350 mg/L for larvae. Rapid mass marking of otoliths in razorback sucker embryos or larvae has great potential for use in stock identification, assessment of stocking success, and life-history studies.

Muth, R. T., and D. E. Snyder. 1995. Diets of young Colorado squawfish and other small fish in backwaters of the Green River, Colorado and Utah. Great Basin Naturalist 55:95–104.

We compared diet of young-of-year Colorado squawfish (*Ptychocheilus lucius),* an endangered cyprinid, with diets of other fish < 75 mm total length (TL) collected from backwaters of the Green River between river kilometers 555 and 35 during summer and autumn 1987. Species included native *Rhinichthys osculus, Catostomus discobolus,* and C. *latipinnis,* and nonnative *Cyprinella lutrensis, Notropis stramineus, Pimephales promelas, Ictalurus punctatus,* and *Lepomis cyanellus.* For each species, diet varied with size and between upper and lower river reaches but not between seasons for fish of similar size. Larval chironomids and ceratopogonids were principal foods of most fishes. Copepods and cladocerans were important in diets of *P. lucius* < 21 mm TL and *L. cyanellus* < 31 mm TL. *Catostomus discobolus* was the only species that ate moderate amounts of algae. Fish (all larvae) were in digestive tracts of only 10 *P. lucius* (21–73 mm TL), about 1% of *P. lucius* analyzed. High diet overlap occurred between some size-reach groups of *P. lucius* and *C. lutrensis, R. osculus, C. latipinnis, L. punctatus,* and *L. cyanellus.* Potential for food competition between young of-year *P. lucius* and other fishes in backwaters appeared greatest with the very abundant *C. lutrensis*.

Muth, R. T., and E. J. Wick. 1997. Field studies on larval razorback suckers in Canyonlands National Park and Glen Canyon National Recreation Area, 1993–1995. Final Report of Colorado State University Larval Fish Laboratory to U.S. National Park Service, Rocky Mountain Region, Denver, Colorado. ***Abstract excerpted from Executive Summary***

Field studies on larval razorback suckers (*Xyrauchen texanus*) were conducted during spring–summer 1993–1995 in reaches of the lower Green River (from Millard Canyon, RK 53.9, downstream to Holeman Canyon, RK 45.1) or middle Colorado River (from the Gooseneck area, RK 58.4, downstream to Lathrop Canyon, RK 37.6) within or bordering Canyonlands National Park and in the lower 47 km of the Colorado River inflow to Lake Powell within Glen Canyon National Recreation Area. Studies and key findings included:

1. Fish collections using floating quatrefoil light traps and seines in quiet-water flooded or backwater habitats (1993–1995).

   - Nonnative minnows (e.g., red shiner *Cyprinella lutrensis*, sand shiner *Notropis stramineus*, and fathead minnow *Pimephales promelas*) dominated all fish collections (76–99% of total catch from each sampling area over all sampling periods). Native fishes collected included larval razorback suckers (185 total – 122, 47, and 1 from the lower Green River in 1993, 1994, and 1995, respectively; 15 from the Colorado River inflow to Lake Powell in 1993), and larval or early juvenile Colorado squawfish *Ptychocheilus lucius* (12 larvae and 133 juveniles total – 12 larvae and 6 juveniles in 1993 and 5 juveniles in 1994 from the Colorado River inflow to Lake Powell in 1993; 1, 36, and 82 juveniles from the lower Green River in 1993, 1994, and 1995, respectively; 3 juveniles from the middle Colorado River in 1994). Of all razorback suckers collected, 168 were captured by light traps and 17 (from the lower Green River) by seines. Colorado squawfish larvae were caught in light traps and juveniles were caught in seines.

   - The collection of razorback sucker larvae from the lower Green River suggests localized spawning.

   - Collections of razorback sucker and Colorado squawfish larvae from the Colorado River inflow to Lake Powell in 1993 suggest that flowing, lotic conditions throughout the inflow are necessary to transport larvae produced in upstream river reaches into inflow nursery habitats.

   - Larval suckers were efficiently and accurately identified alive in the field, but procedures for successfully transporting wild razorback sucker larvae caught in remote areas (e.g., lower Green River) to rearing facilities require further development.

2. Description of the diet of adult nonnative red shiners captured from the lower Green and middle Colorado rivers (1994).

   - Digestive tracts of 22 adult red shiners (5% of those examined) contained cypriniform fish larvae, most were catostomids. Insects, including parts, chironomid larvae, simulid pupae, and corixids, were the principal identifiable food items. Adult red shiners may be an important predator on native fishes in the Colorado River basin, especially in habitats with low invertebrate forage during spring and early summer.

3. Initial evaluation of a method to partially block access of adult red shiners into portions of important nursery habitats for larval razorback suckers in the lower Green River using net exclosures (1995).

- Netting effectively blocked access of adult red shiners into exclosed portions of nursery habitats while allowing passage of sucker larvae; results suggest that this method of nonnative fish control could be adapted for broader-scale use.

4. Field marking of sucker larvae using techniques developed in the laboratory for incorporating fluorescent chemicals into otoliths (1995).

   - Laboratory techniques for marking otoliths in larval razorback suckers were successfully applied to sucker larvae in the field. Otolith aging of wild-caught razorback sucker larvae can be used to determine growth rates and exact time of spawning, data which can then be used to document environmental parameters associated with spawning and nursery habitats and evaluate factors influencing growth and survival of larvae.

Muth, R. T., G. B. Haines, S. M. Meismer, E. J. Wick, T. E. Chart, D. E. Snyder, and J .M. Bundy. 1998. Reproduction and early life history of razorback sucker in the Green River, Utah and Colorado, 1992–1996. Final Report of Colorado State University Larval Fish Laboratory to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 34) ***Abstract excerpted from Executive Summary***

This report integrates results of studies conducted during spring and early summer 1992–1996 on larval razorback suckers (*Xyrauchen texanus*) in selected reaches of the middle Green River (from mouth of the Yampa River, river kilometer [RK] 555.1, downstream to the Ouray Bridge, RK 399.4), Utah and Colorado, or lower Green River (downstream of Green River, Utah, to RK 40.7), Utah. Studies included two Colorado River Recovery Implementation Program projects (numbers 34 and 38, Chart et al. 1998) and research sponsored by the National Park Service (Muth and Wick 1997). Objectives were to (1) develop effective methods for collecting razorback sucker larvae in rivers, (2) document reproduction by razorback suckers, (3) evaluate the distribution and relative abundance of larval razorback suckers, (4) associate razorback sucker spawning dates with main-stem discharges and temperatures, and (5) estimate growth rates and describe the diet of larval razorback suckers in nursery habitats.

Larval razorback suckers were collected in each year of sampling from the middle (1992–1996) and lower (1993–1996) Green River. These captures represent the first confirmed reproduction by the species in the middle Green River since 1984 and the first ever records of razorback sucker larvae in the lower Green River. A total of 1,735 larvae was caught in the middle Green River and 440 in the lower Green River. Of all individuals collected from the middle Green River, 1,651 were captured by light traps, 69 by seines, 12 by drift nets, and 3 by dip nets. In the lower Green River, 415 specimens were caught by light traps and 25 by seines.

Catches of larval razorback suckers were highly variable among years and reaches. Numbers captured per year ranged from 20 in 1992 to 1,217 in 1994 for the middle Green River and

from 5 in 1995 to 222 in 1996 for the lower Green River. In the middle Green River, the Escalante (711 larvae), Jensen (700), and Ouray (318) reaches combined produced 99% of the total catch. Only six individuals were caught in the Echo Park reach, and none was captured from the Island-Rainbow Park reach. In the lower Green River, 363 larvae were collected from the lower Labyrinth-upper Stillwater Canyon reach, 76 from the San Rafael River confluence reach, and 1 larva was caught in the Green River Valley reach.

Capture dates of razorback sucker larvae over all years ranged from 16 May to 21 July in the middle Green River and from 7 May to 9 July in the lower Green River. In most years, larvae were first collected 20–30 d after the earliest estimated date of spawning and were usually most abundant in samples collected before mid-June. Earlier first occurrence of larvae in collections from the San Rafael River confluence or lower Labyrinth-upper Stillwater Canyon reaches compared to collections from the middle Green River suggested that razorback suckers reproduced in the lower Green River each year during 1994–1996.

Estimated initiation of spawning by razorback suckers in each year during 1993–1996 was generally associated with the beginning of spring-runoff flows and was probably triggered by a suite of interacting environmental cues that could not be detected by analysis of individual water temperature and discharge parameters. Duration of spawning in either the middle or lower Green River varied among years but usually spanned 4–6 weeks each year. Spawning occurred during increasing and highest spring flows and encompassed a wide range of mainstem mean daily discharges and instantaneous daily water temperatures.

The majority of larval razorback suckers (11–18 mm total length, TL) analyzed for diet had eaten, and mean percent fullness of digestive tracts increased with fish length (ranged from 35 to 65%). Principal dietary components were early instar chironomid larvae, small cladocerans, rotifers, algae, and organic and inorganic debris. Estimated mean daily growth of razorback sucker larvae less than 35 d old collected from either river section during 1993–1996 was lowest in 1994 (0.31 and 0.27 mm TL/d for the middle and lower Green River, respectively) and greatest in 1996 (0.35 and 0.33 mm TL/d). Over all years, specimens from the middle Green River grew 6–21% faster than those from the lower Green River. Although food abundance appeared adequate to meet the minimum nutritional requirements for larval survival, the growth potential of razorback sucker larvae is greater than we observed. Poor growth can significantly reduce the survival of fish early life stages if size-dependent processes regulate year-class success. Extremely low survival was suggested by the apparent disappearance of larval razorback suckers from Green River nursery habitats by early or mid-July each year.

Restoring access to warm, productive floodplain wetlands to serve as growth and conditioning habitats appears crucial for recovery of self-sustaining razorback sucker populations in the Green River. Reestablishment of some river-wetland connections by breaching levees along the middle Green River is a promising start, but substantial increases in floodplain inundation will require management of spring-peak releases from Flaming Gorge Dam in wet years when discharge is high to provide the flows necessary for over-bank flooding.

Orchard, K. L., and J. C. Schmidt. 2000. A geomorphic assessment of the availability of potential humpback chub habitat in the Green River in Desolation and Gray Canyons, Utah. Report A *in* Flaming Gorge studies: reproduction and recruitment of *Gila* spp. and Colorado pikeminnow (*Ptychocheilus lucius*) in the middle Green River. Final Report of Utah Division of Wildlife Resources to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 39)

The size and number of low-velocity eddies that may be preferred habitat for the endangered humpback chub (*Gila cypha*) in the Green River in Desolation and Gray Canyons changes with discharge and has changed since the early 1900's. We determined the present extent and distribution of these habitats by mapping low-velocity eddies at a scale of 1:5000 at 5 or 6 discharges between 2,100 and 27,000 cfs in four 8-km reaches that are regularly sampled by the Utah Division of Wildlife Resources. We also mapped the surficial geology of these study reaches and the distribution of bed substrate that are emergent at 2,000 cfs. We analyzed the distribution of these areas within a geographic information system. The availability of habitat prior to completion of Flaming Gorge Dam was estimated by matching old oblique photographs, analyzing old aerial photos, and recomputing habitat availability prior to channel change.

The total area of low-velocity eddies, when summed for the 4 study reaches, does not change with discharge, but the relative distribution of these eddies among the 4 study reaches does change. Also, the type of eddies changes with discharge. At low discharge, the greatest proportion of the total area of low-velocity eddies occurs as small shoreline eddies, but the greatest proportion occurs in a few large eddies at higher discharges. At low discharge, the river bank is highly contorted and is dominantly bare sand and gravel. At high discharge, the river bank has a simpler shape, and much of the shoreline is inundated vegetation.

The Green River channel is 19% narrower today than it was in the 1920's, and riparian vegetation has established itself at low elevations and on formerly active mid-channel islands. We estimate that the substrate of most nearshore habitats was sand or gravel prior to channel narrowing.

For purposes of developing flow recommendations, our results must be integrated with the results of ecological studies which identify the relative importance of the different habitats in the life history of the target species.

Pick, T. A. 1996. Peak flow computations, Green River tributaries below Flaming Gorge Dam, Colorado and Utah. Memorandum dated June 18, 1996, U.S. Bureau of Reclamation Technical Service Center, Denver, Colorado. ***Abstract excerpted from results and conclusions***

Streamflow records for U.S. Geological Survey gages on six tributary streams in the Green River basin were evaluated by Pick (1996) and the magnitude of flood flows for a range of occurrence frequencies was determined. The gages used in this analysis were: (1) Yampa River near Maybell, Colorado; (2) Little Snake River near Lily, Colorado; (3) Duchesne River near Randlett, Utah; (4) White River near Watson, Utah; (5) Price River at Woodside, Utah; and (6) San Rafael River near Green River, Utah.

For the stations with major upstream reservoirs, especially the Duchesne River with four upstream reservoirs, no attempt was made to remove the effects of regulation from the record. Also, it was assumed that log-Pearson type III was the proper distribution to be used in analysis of the flood records for these gages.

Proebstel, D. S. 1998. Analysis of larval collections of razorback suckers based on restriction enzyme digestion of PCR amplified regions of mitochondrial DNA. Final Report of Colorado State University Department of Fishery and Wildlife Biology to U.S. National Park Service Cooperative Parks Study Unit, Fort Collins, Colorado. ***Abstract excerpted from results and conclusions***

This study was conducted to determine if molecular-genetic techniques could be used to verify the identity, based on morphological criteria, of larvae of white sucker (*Catostomus commersoni*), bluehead sucker (*C. discobolus*), flannelmouth sucker (*C. latipinnis*), and razorback sucker (*Xyrauchen texanus*). Molecular-genetic techniques may be useful because traditional taxonomic approaches have sometimes yielded inconclusive identification of these larvae, particularly larvae less than 15 mm total length. The genetic technique employed was restriction-fragment-length polymorphisms from enzyme digestion of regions of mitochondrial DNA amplified by polymerase chain reactions. Specimens of each species that were analyzed included wild-caught larvae from the Green River, Utah, identified by morphological criteria and known identity controls. For all individuals successfully analyzed, there was complete concordance in identity between classical taxonomic methods and molecular-genetic techniques. Primary conclusions were 1) molecular methods are useful for identification of larval white, bluehead, flannelmouth, and razorback suckers, and 2) provisional identifications based on morphological criteria were correct.

Rakowski, C. L., and J. C. Schmidt. 1999. The geomorphic basis of Colorado pikeminnow nursery habitat in the Green River near Ouray, Utah. Report A *in* Flaming Gorge Studies: Assessment of Colorado pikeminnow nursery habitat in the Green River. Final Report of Utah Division of Wildlife Resources to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 33)

Nursery habitat availability is considered a bottleneck to successful recruitment of Colorado pikeminnow *(Ptychocheilus lucius).* Detailed geomorphic studies were conducted in a 1.5-km reach to examine channel response to flows and the geomorphic setting of nursery habitats during a 2-year period. Videography was used to extend relationships in the 1.5-km reach to a longer 10-km reach.

Nursery habitat availability varied yearly with little persistence in location or geomorphic setting of individual habitats for the 2 years of this study. A small number of habitats provided most of the area of high-quality (i.e., deep) habitat, and most of the total area of habitat was formed by three geomorphic classes. Although the 1993 flood reduced the area of available habitat, area of deep habitat increased. The 1994 low-peak flood increased the area of habitat, but most habitats were shallow.

The 1993 and 1994 multi-peaked habitat availability curves for the 1.5-km-reach bank-attached bar were the result of the superposition of curves from habitats in each geomorphic classification, and showed that the discharge that maximized habitat availability changed yearly. A complexity index was evaluated for the 10-km reach as a surrogate for habitat availability. Total base-flow habitat availability was significantly correlated to the complexity index, but deep habitat availability was not.

Measured channel topography was used as input to a flow and sediment transport model. Simulated hydrograph runs produced greater bank-attached bar aggradation and thalweg scour than steady flows, although some unrealistic patterns of scour occurred.

New flow recommendations must include occasional high flows sufficient to rebuild channel topography. Flaming Gorge Dam releases should be used to augment the Yampa River flood peak, but not increase low flood-peak duration. The conceptual model for habitat availability developed here may be used to target the formation and availability of habitats. Base flow recommendations designed to maximize habitat availability should be evaluated annually. Winter flows should be reevaluated for their negative effects on habitat.

Ruppert, J. B., R. T. Muth, and T. P. Nesler. 1993. Predation on fish larvae by adult red shiner, Yampa and Green Rivers, Colorado. Southwestern Naturalist 38:397–399. (Recovery Program Project 12-9) ***Abstract excerpted from results and conclusions***

The objective of this study was to document predation on fish larvae, particularly larvae of native fishes, by nonnative adult cyprinids or juvenile centrarchids or ictalurids collected from ephemeral shoreline embayments near the confluence of the Green and Yampa rivers, Colorado, in early summer. Collections with fine-mesh seines (1.6-mm-square mesh) were made on 30 June and 2, 14, 19, and 25 July 1991. Sampling on 30 June was at 1600–1800 hours, and on other dates at 0000–0200, 0400–0600, 1200–1400, 1600–1800, and 2000–2200 hours. Nonnative fishes collected and analyzed were yearling channel catfish *Ictalurus punctatus* (*N* = 17; 51–144 mm total length, TL) and adult red shiners *Cyprinella lutrensis* (*N* = 184; 36–79 mm TL), sand shiners *Notropis stramineus* (*N* = 47; 30–65 mm TL), fathead minnows *Pimephales promelas* (*N* = 42; 32–60 mm TL), and redside shiners *Richardsonius balteatus* (*N* = 176; 36–77 mm TL). Fish larvae (*N* = 58; 1–9 per digestive tract) were found in 15% of the red shiners collected during daylight or dusk on 30 June and 2 and 14 July; no larvae were detected in digestive tracts of the other species. Most of the fish larvae found were too digested for species identification or accurate length measurements, but all were cypriniforms (mostly catostomids) and probably less than 16 mm TL. Seven fish larvae, 11–13 mm TL, were identified as native bluehead sucker *Catostomus discobolus*. The high incidence of fish larvae ingested by red shiners suggests that this widespread and abundant species may be an important predator on native fishes in the Colorado River system. The degree of predation may be influenced by the abundance of alternative invertebrate prey and may be especially severe during spring and early summer in ephemeral nursery habitats with fluctuating water levels.

Schmidt, J. C. 1994. Compilation of historic hydrologic and geomorphic data for the upper Colorado River basin. Annual Report of Utah State University Department of Geography and Earth Resources to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 37) ***Abstract excerpted from results and conclusions***

Preliminary results of ongoing investigations of the geomorphology and hydrology records of the Green River Basin are:

1. The magnitude of the annual peak discharge of the Green River upstream from the Yampa River has decreased about 60% from the 1923–1962 period to the period following closure of Flaming Gorge Dam. At Jensen and Green River, Utah, the changes have been about 25%, depending on the recurrence of the flood being evaluated. Floods on the Yampa River were unchanged during the same periods.

2. The highest floods of this century occurred in the early part of the century. Instantaneous peak discharge at Green River, Utah, exceeded 60,000 ft^3/s (1,698 m^3/s) in 1897, 1909, 1917, and 1921. Peak flows at Greendale are estimated to have exceeded 20,000 ft^3/s (566 m^3/s) in 1899, 1918, and 1921. These floods are unprecedented; the fact that floods of this magnitude do not occur at present may be related to climatic change and be unrelated to the existence of dams. The effects of these floods on habitat availability have not been evaluated.

3. The bed at the Greendale gage aggraded 0.3 ft between 1961 and 1987.

4. The bed at the Jensen gage has not changed in elevation since 1948. Speculation about channel degradation in the Razorback bar and Escalante Bottoms area is not supported by these findings.

5. Degradation of about 0.3 ft of the channel bed at Ouray occurred between 1951 and 1966. It is unlikely that these changes are related to Flaming Gorge Dam.

6. Prior to closure of Flaming Gorge Dam, the Green River near Greendale, Utah, was covered by ice between 3 and 5 months per year. The last year that ice cover was reported at this gage was 1958.

7. Between the winters of 1946–47 and 1960–67, the average duration of ice cover was 3.6 months near Jensen. Since that time, the duration has decreased to 0.8 months. At Ouray, the average duration of ice cover was 3 months between 1951 and 1965.

8. A new floodplain, in apparent equilibrium with reduced floods has developed in the Uinta Basin, especially in the Ouray National Wildlife Refuge. This floodplain is regularly inundated but the area extent of these surfaces is an order of magnitude less than the pre-dam floodplain. It appears that significant inundation of the alluvial valley of the Green River may not have regularly occurred since the 1920's.

9. Significant channel narrowing in Lodore Canyon has occurred since closure of Flaming Gorge Dam. Numerous eddy bars have been vegetated and backwater habitats may have been lost.

Schmidt, J. C. 1996. Geomorphic control of the distribution of age-0 Colorado squawfish in the Green River in Colorado and Utah. Draft Manuscript. Department of Geography and Earth Resources, Utah State University, Logan.

Regional geology controls the geomorphic organization of the Green River in Colorado and Utah and produces a series of river segments that are either restricted meanders, fixed meanders, or canyons with abundant debris fans. The distribution of channel planform controls the distribution of shoreline complexity, and there is no systematic downstream change in channel planform or in shoreline complexity.

Backwater habitats, which typically are abundant where complexity is high, are used as nursery areas by age-0 Colorado squawfish. Field measurements of channel and bar topography, air photo and geographic information system analysis, and simulation modeling show that the location of critical nursery habitat segments of the river is ultimately determined by channel geomorphology. Longitudinal dispersion establishes a system-wide pattern wherein downstream segments have higher age-0 populations, but restricted meandering reaches have proportionally higher populations than predicted solely by longitudinal dispersion. Streamflow at the time of larval drift also affects population and distribution. The interaction of hydrology, geomorphology, and the characteristics of spawning and larval drift must be understood collectively if operations of Flaming Gorge Dam are to be adjusted to maintain the present distribution of river segments critical as nursery habitats in the Green River.

Schmidt, J. C., and D. M. Rubin. 1995. Regulated streamflow, fine-grained deposits, and effective discharge in canyons with abundant debris fans. Pages 177–195 *in* J. E. Costa, A. J. Miller, K. W. Potter, and P. R. Wilcock, editors. Natural and anthropogenic influences in fluvial geomorphology. AGU Geophysical Monograph 89. ***Abstract excerpted from results and conclusions***

The debris fan-eddy complex is the fundamental geomorphic channel unit in canyons with abundant debris fans. This assemblage includes, in a downstream direction, a river segment of ponded flow that has a low downstream velocity and that is controlled by a downstream channel constriction, a constricting debris fan, eddies and eddy bars, and a gravel bar. This assemblage occurs at nearly every tributary mouth where debris fans constrict the river. Such tributaries exist along many, but not all, of the narrow canyons of the Green and Colorado Rivers. Reaches affected by debris fans are steeper, have higher stream power per unit bed area, and have coarser beds than other narrow canyons of the same river system. The extent of each channel element varies from site to site.

Schmidt, J. C., K. L. Orchard, and S. P. Holman. 1996. Spatial and temporal patterns of habitat availability in Desolation and Gray Canyons. Report of Utah State University Department of Geography and Earth Resources to Utah Division of Wildlife Resources, Salt Lake City, Utah.

Channel geometry, shoreline composition and hydrologic units were mapped and measured over a range of discharges from 2100 to 27,000 ft^3/s (59 to 764 m^3/s) in Desolation and Gray Canyons of the Green River, Utah. Four geomorphic reaches were identified in coordination with fish sampling. In general, cobble-bedded areas showed little or no channel change for the range of discharges experienced. Sand-bedded areas showed greater variability with discharge. Greatest depths occurred in the thalwegs of downstream flow next to recirculation zones. Debris fans in Desolation Canyon were noted as low gradient and very large with only 25% of surface area within an active zone. In Gray Canyon, debris fans were steeper in gradient. Gravel bars were noted to be abundant in all reaches. The gradient of debris fans dictates the relationship between downstream eddy size and flow. As flow increases, eddy size increases until the debris fan is overtopped at which flow the eddy does not exist. In Desolation Canyon, debris fans were overtopped at relatively low flows compared to Gray Canyon. Hence, eddies occur over a greater range of flows and increase in size more in Gray than in Desolation Canyon. Shoreline composition was predominately sand, silt and mud (fine-grained alluvium) at base flows with vegetation comprising the smallest portion of shoreline and gravel, talus and debris blow being approximately equal. As discharge increases, alluvium was inundated and shorelines composition shifted to more vegetation. At bankfull, 62% of the shoreline comprised vegetation. Linear length of shoreline decreased with increasing discharge but was not greatest at the lowest discharge. Hence, shoreline sinuosity is maximized as some intermediate discharge. Comparison of historic and recent photographs demonstrated that shoreline vegetation (tamarisk and willow) increased in all reaches. Mid-channel islands and sand bars that were historically transient by nature have become stabilized by the combination of increased vegetation and reduced flooding. Tributary inflows, like the Price River, are notably aggraded and overrun with vegetation due to a reduction in tributary flows.

Schmidt J. C., K. L. Orchard, and S. P. Holman. 1996. Spatial and temporal patterns of habitat availability in Desolation and Gray Canyons. 1995 Annual Report and 1996 Field Progress Report, Department of Geography and Earth Resources, Utah State University. Logan.

Available shoreline habitat along the Green River in Desolation and Gray Canyons is strongly influenced by geology and discharge although the relationship between the three has not been readily apparent. To better associate the two, we established four geomorphic study reaches within the canyons. Within each reach, a series of cross sections was measured at different discharges. Surficial geology of the river corridor was mapped, and historic oblique photos were matched to establish the geomorphic organization of the canyon and assess changes that have occurred over the past century. Maps were also made of the distribution of eddies, low-velocity zones, and the distribution of shoreline habitat. These maps were repeated at several discharges including base flow and bank full discharge.

Preliminary results show that low-velocity zones occur predominantly in the lee of obstructions caused by debris fans. Debris fans in Desolation Canyon are predominantly expansive and of low gradient. Only the small portion of the fan that is active delivers sediment that restricts flow and causes rapids and eddies, while the main fan is so large that it acts more as a meander bend as the river flows around the fan. As discharge increases the total area of eddies increases, however, at bankfull discharge many of the relatively small active portions of the fans are overtopped, and eddy frequency decreases. Although very large debris fans dominate the river corridor, fine-grained alluvium is the most abundant bank material at low discharge, and vegetated fine-grained alluvium dominates at higher flows.

Smith, G. R. 1997. Yampa and Green River physical data. Undated Memorandum, U.S. Fish and Wildlife Service, Denver, Colorado. ***Abstract excerpted from results and conclusions***

Water temperature data were collected by the U.S. Fish and Wildlife Service at six sites on the Green River during 1987–1997. The temperature of the Yampa River was also monitored during this time period as well as one additional site on the Green River from 1994 to 1997. Monitoring at this latter site was conducted by Colorado State University. These data are accessible through the Division of Water Resources, U.S. Fish and Wildlife Service in Denver, Colorado.

Snyder, D. E. 1997. Effects of the fish anesthetic tricaine on larval and early juvenile razorback sucker, *Xyrauchen texanus*. Final Report of Colorado State University Larval Fish Laboratory to U.S. National Park Service Cooperative Parks Study Unit, Fort Collins, Colorado.

Field identification and handling of live fish larvae often requires use of an anesthetic to induce temporary paralysis. To assess the effectiveness of aqueous solutions of the anesthetic tricaine (Finquel™) for rapid but safe immobilization of larval and early juvenile razorback sucker, I tested lab-reared protolarvae at 0 (controls), 50, 100, and 200 mg/L, mesolarvae at 0, 6.25, 12.5, 25, 50, 100, 200, 400, and 800 mg/L, and recently transformed juveniles at 0, 50, 100, 200, and 400 mg/L. For each of three trials per treatment, I recorded times to loss of: equilibrium, reflex response (full immobilization except for breathing), and breathing motions. After full loss of equilibrium by all eight or ten fish in a trial (or 5 min if fish remained upright), I retained half in the anesthetic for an additional 5 min and the other half for 15 min. I then transferred the fish to freshwater, recorded recovery times, and monitored survival for 4 d. For this investigation, I considered optimal immobilization and recovery times to be less than 1 and 10 min, respectively. Tricaine concentrations of 50 mg/L or less failed to immobilize completely all fish in any treatment and 100 mg/L was borderline for protolarvae. Only the 200 mg/L treatment for protolarvae met the optimal criteria. Concentrations of 100 and 200 mg/L best approached the criteria for mesolarvae; likewise for early juveniles except that 15-min exposures were not safe for juveniles at either concentration, or even for 5 min at 400 mg/L. Except for juvenile exposures much over 5 min, median concentrations of about 150 mg/L are mostly likely to approximate the goal for larvae and early juveniles and are therefore recommended. For early juveniles, concentrations somewhat less than 100 mg/L may immobilize the fish without loss of breathing and thereby allow exposures of 15 min or longer, but immobilization will likely require a few minutes.

For mesolarvae, and probably for protolarvae, concentrations of 400 and 800 mg/L were safe, even for 15-min exposures, and resulted in almost instantaneous immobilization but much longer recovery times. As a corollary to the latter results and other observations, high doses of tricaine, at least up to 1,600 mg/L, are ineffective for euthanasia of razorback sucker and probably other fish larvae not yet relying heavily on gills for respiration.

Snyder, D. E., and S. M. Meismer. 1997. Effectiveness of light traps for capture and retention of larval and early juvenile *Xyrauchen texanus* and larval *Ptychocheilus lucius* and *Gila elegans*. Final Report of Colorado State University Larval Fish Laboratory to U.S. National Park Service Cooperative Parks Study Unit, Fort Collins, Colorado.

Light traps are used to capture the larvae of many fishes. To assess the potential of floating, low-intensity, quatrefoil-style light traps for capture of the larvae or early juveniles of endangered Colorado River basin fishes, provide guidelines for trap use, and better interpret field results, we conducted experiments in 1.2-m diameter tanks under light-excluding tents. For each capture trial, 50 laboratory-reared larvae or (for razorback sucker *Xyrauchen texanus* only) 25 juveniles were released into a tank and allowed to acclimate through simulated daylight, dusk, and full darkness before traps were set for 1, 4, or (for razorback sucker larvae only) 8 h. In corresponding retention experiments, fish were placed in trap catch basins and allowed to calm before traps were placed in tanks. Mean capture percentages (MCPs) for larvae in 1 and 4-h trials were 13 to 36% for razorback sucker (33 to 44% in 8-h trials), 3 to 15% for Colorado squawfish *Ptychocheilus lucius*, and 5 to 30% for bonytail *Gila elegans*. MCPs usually, but not always, increased with set duration for larvae. For early juvenile razorback suckers, maximum MCP, 51%, occurred within 1 h. Once in the trap, most larvae stayed; mean retention percentages (MRPs) were 85 to 99% for razorback sucker larvae in 1, 4, and 8-h trials, and 95 to 99% for Colorado squawfish larvae in 1 and 4-h trials (bonytails were not tested for retention). Retention of juvenile razorback suckers was notably less with MRPs of 65 to 73%. For fish in close proximity to the trap, these results suggest that the light traps tested are at least moderately effective in clear water for the capture and retention of razorback sucker and bonytail larvae and even better for the capture of early juvenile razorback suckers.

Additional experiments were conducted with razorback suckers. With trap lights off, few or no fish were captured and MRPs were lower, strikingly so for protolarvae with only 16% retention in 4-h trials. Light is critical for the effective capture and retention of fish larvae. Under simulated dusk, 1-h MCPs were lower than during night trials, but not significantly different. Setting traps prior to night fall might increase the ultimate number of fish collected but reduce catch per unit time. Under simulated dawn, 1-h MRPs dropped to 69% for protolarvae but remained 99% for postflexion mesolarvae. Traps should probably be retrieved before dawn to avoid significant losses of at least small larvae. In 1-h turbid-water trials, MCPs were 2.6 to 2.8 times greater for larvae but 70% less for juveniles in 50 to 75 FTU water than in clear water. For fish in close proximity to the trap, effectiveness significantly increased for larvae in turbid water but decreased for early juveniles. Although maximum body width of the larger postflexion mesolarvae approximated 2 mm, MCPs and MRPs for those larvae did not change significantly when 4-mm silt traps were used instead of 2-mm traps. However, early juveniles were unable to enter 2-mm traps. Maximum total length for capture of razorback suckers by 2-mm slit traps was between 20 and 27 mm. MCPs for postflexion mesolarvae did not change significantly when tested in a comparable trap with 300 times greater light intensity at trap perimeter. MCPs for early juveniles dropped by over two-thirds to 19% in trials using a larger three-lobed light trap with comparable low-light intensity and to just 8% with 500 times greater light intensity. Dramatically increasing trap light intensity did not affect the capture of postflexion mesolarvae but significantly reduced the catch of early juveniles. Differences in trap design can affect the number of early juveniles captured.

Stanford, J. A. 1994. Instream flows to assist the recovery of endangered fishes of the Upper Colorado River basin: review and synthesis of ecological information, issues, methods and rationale. U.S. Fish and Wildlife Service, Denver, Colorado. FLBS Open File Report 130-93. ***Abstract excerpted from results and conclusions***

The purpose of this study was to review the science pertaining to the issue of flow provision, to identify critical uncertainties and to provide recommendations for determining the instream flow needs of the endangered fishes.

Studies to date strongly indicate that truncation of peak flows and higher, fluctuating base flows (loss of seasonality) resulting from river regulation have altered complex biophysical processes (detailed herein) that form and maintain low velocity habitats required for survival of the various life history stages of the fishes. An ecological tradeoff apparently exists: very high flows are needed occasionally to produce habitats that the fish need to survive, but at the expense of reproductive success.

Based on review of the ecological information and recognizing the problems in the methodological approaches that were used to derive flow recommendations, several key uncertainties appear to be critical to the goal of establishing flow regimes that will ultimately recover the endangered fishes:

- Flow seasonality and its correlates (e.g., temperature and physical habitat) may not be the factor(s) limiting recovery of the native fishes.

- Given the high societal value placed on tailwater trout fisheries, and the high priority placed on meeting entitlements under the Colorado compact and current water law (i.e., the “law of the river”), water volume in the Colorado and Green Rivers may be insufficient to produce flows required to recover the fishes.

- Channel and floodplain morphology in time and space is not a simple flow-area relationship and complex interactions not yet fully understood may emerge that will compromise recovery of the fish.

- What is the tradeoff between propensity of endangered fish larvae to drift downstream and the need for high flows to maintain connectivity between the channel and backwaters and wetlands?

- Can food webs re-establish in key low velocity habitats (backwaters) to the extent needed to recover the fishes, given the windows permitted or needed for hydropower operations?

- Can the endangered fishes expand their range and productivity given the downstream extension of cold water environments caused by regulation, and is the locality of the

transition zone between cold and warm reaches likely to stay constant as deregulated flow regimes are implemented?

- Interactions with nonnative fishes may limit recovery of endangered fishes regardless of flow provisions.

The report concludes with recommendations that couple management action (implementation of interim flow regimes) with additional study to resolve the uncertainties presented above. The suite of recommendations constitute an ecosystem approach to resolution of flows needed to protect and enhance the endangered fishes of the upper Colorado River basin. In essence, these recommendations constitute a new, holistic instream flow methodology.

- Implement interim flows that re-establish seasonality with spring peaks that approach the amplitude and frequency of preregulation events and summer and winter base flows with daily changes (not daily volume) limited to near preregulation conditions (likely no more than about 5% per day).

- Provide common understanding of water availability so that interim flows can be provided in relation to precipitation and legal flow abstraction in each subbasin.

- Improve the standardized monitoring program as a mechanism to evaluate effectiveness of interim flows by adding a community ecology perspective.

- Diversify the research program to resolve critical uncertainties associated with interim flows.

- Implement a peer review process to insure that research and monitoring objectives are based on solid science and are responsive to the need to resolve uncertainties associated with the interim flows.

- Implement a management plan that can adaptively change the interim flows as new implications from monitoring and research are forthcoming.

The recommended methodology needs unambiguous endorsement to be successful. Success or failure will be judged by long-term trends in the populations of the endangered fishes.

Trammell, M. A., and T. E. Chart. 1999. Colorado pikeminnow young-of-the-year habitat use, Green River, Utah, 1992–1996. Report C *in* Flaming Gorge Studies: Assessment of Colorado pikeminnow nursery habitat in the Green River. Final Report of Utah Division of Wildlife Resources to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 33)

This nursery habitat study was conducted from 1992 to 1996 under the auspices of the Recovery Implementation Program, to further define Colorado pikeminnow use of habitat. The relationships between peak and sampling flows, habitat availability, temperature, Colorado pikeminnow catch and growth rates, and density of sympatric non-native cyprinids were examined. The objectives of this study included: 1) determine the relationship between availability, formation, and maintenance of Colorado pikeminnow nursery habitat and test release flows from Flaming Gorge Dam, 2) describe the relationship between nursery habitat types available to and selected by Colorado pikeminnow, 3) describe the relationship between degree-day accumulation in main channel and nursery habitat areas, 4) determine the relationship between degree-day accumulation in all potential nursery habitat areas and those utilized by young Colorado pikeminnow, 5) determine the relationship between the quantity of nursery habitats available in the summer period to the number of young Colorado pikeminnow present in nursery habitats during the autumn period, 6) determine the usefulness of video imagery as a predictor of year class strength of Colorado pikeminnow, 7) refine the interpretation of video so that "quality" nursery habitats can be distinguished, and 8) compare intensive sampling data and the concept of habitat utilization to standardized monitoring data to assess a) ways of refining standardized monitoring procedures and b) ways of making greater use of the data currently being collected.

Colorado pikeminnow prefer backwater habitats that are formed behind large sandbars from scour channels, and are larger, deeper and more persistent than other habitats. Non-native cyprinids also preferred this habitat. All types of habitat including quality habitat increased in quantity during low water years, and decreased in high water years. There were slight decreases associated with higher sampling flows. Non-native cyprinids were positively associated with increased habitat availability, while Colorado pikeminnow were negatively associated. Total degree day accumulation was higher in low water years, which in turn was positively correlated with high growth rates for pikeminnow, and with high overwinter survival rates. The density of non-native cyprinids was negatively correlated with Colorado pikeminnow catch rates. Colorado pikeminnow are limited more by the presence of non-native cyprinids than by habitat availability in the lower Green River. We recommend managing the river system for a variety of flow scenarios to emulate the natural hydrograph. The standardized monitoring program sampling protocol is sufficiently representative of Colorado pikeminnow annual trends. We recommend no changes.

Valdez, R. A. 1995. Synthesis of winter investigations of endangered fish in the Green River below Flaming Gorge Dam. Final Report of BIO/WEST, Inc. to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 18-11)

Recent investigations by Valdez and Masslich (1989) and Wick and Hawkins (1989) on radiotagged adult Colorado squawfish and razorback suckers in the Green River and Yampa River revealed a fidelity for overwintering sites in moderately deep, low-velocity habitats. Both species were locally active, but rarely left a habitat, except during flow changes or to avoid ice jams and frazil ice masses. Low, relatively stable winter flows are recommended to stabilize low velocity habitats, allow formation of a persistent ice cover to insulate flows from supercooling, dampen moderate fluctuations, and minimize incidence of ice jams and frazil ice. Further research is recommended to ascertain needs of other life stages of Colorado squawfish, razorback suckers, humpback chub, and other native species. Recommended studies include (1) a physical model of ice processes, (2) assessment of flow regulation and ice on overwinter nursery habitat, (3) valuation of physiological effects of supercooled water on survival of age-0 Colorado squawfish, (4) assessment of Colorado squawfish nursery habitat, (5) estimate of overwinter survival of age-0 Colorado squawfish, (6) survey of the Lake Powell inflow for Colorado squawfish, (7) evaluation of winter and spring flows on movement, dispersal and survival of young Colorado squawfish, and (8) assessment of predation on age-0 Colorado squawfish in supercooled winter conditions.

Valdez, R. A., and B. R. Cowdell. 1999. Effects of flow regulation and ice processes on overwinter nursery habitat of age-0 Colorado pikeminnow in the Green River below Flaming Gorge Dam, Utah. Final Report of BIO/WEST, Inc. to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project FG-10)

Low survival of age-0 Colorado pikeminnow *(Ptychocheilus lucius)* and low recruitment to adulthood are primary factors that contribute to the endangerment of this indigenous Colorado River Basin fish species. Low overwinter survival in the Green River, Utah, may be related to changes in ice processes since completion of Flaming Gorge Dam in 1964. Ice conditions were evaluated in nursery backwaters during winters of 1993–94 and 1994–95 to determine if availability and persistence of these overwinter habitats are related to ice development and breakup processes linked to dam operations. We tested the hypothesis that a post-dam decrease in frequency of stable river ice cover has led to increased occurrence of ice jams and frazil ice that destabilize nursery backwaters, causing the young fish to abandon these habitats at increased risk of predation and presumed energy expenditure.

Ice conditions were studied in one of two primary nursery areas of Colorado pikeminnow for two winters during special releases from Flaming Gorge Dam; i.e., high fluctuating releases in 1993–94 and low stable releases in 1994–95. Both winters were relatively mild and ice development was not as extensive as observed in previous colder winters. An ice cap was more persistent (42 days) during low stable releases than during high fluctuating releases (5 days), providing evidence of a link between dam operations and ice cap formation and persistence. These observations were consistent with 47 years of historic records in which an ice cap formed on the middle Green River in 100% of pre-dam years (18) when flow was relatively stable, but in only 48% of post-dam years (14 of 29) under fluctuating hydropower releases. Warmer, high-volume, fluctuating dam releases have precluded ice cap formation in the Green River nursery habitat area in all but the coldest winters, disrupting the otherwise stable winter riverine environment created by a persistent ice cap and naturally stable winter flows.

Despite the different ice cap conditions observed during the 2 years of special releases, the percentage of backwaters that became unsuitable as nursery habitat in 1993–94 (50%) and 1994–95 (56%) was similar. We attribute similar losses of backwaters to mild air temperatures in both winters that precluded establishment of a thick, stable ice cap resulting in periodic and frequent ice breakup. Of 14 and 9 backwaters surveyed in the two winters, 43% and 34%, respectively, became flow-through channels as a result of ice jams, and 7% and 22%, respectively, were reduced in size or depth by collapsing ice lenses or thickened shoreline ice. Backwaters were considered suitable as long as they retained at least 30 m^2 surface area, 0.3 m depth, were above -0.5^oC water temperature, and had at least 5 mg/L dissolved oxygen-parameters believed to be important for survival of age-0 Colorado pikeminnow.

This study indicates that a stable ice cap is more likely to form on the Green River under relatively stable low releases than under high-volume fluctuating flows during mild winters. Additional studies are needed to determine if this relationship holds true during colder winters. Maintenance of preceding summer and fall dam releases are recommended to maintain nursery backwaters through the winter period. This flow recommendation is based on the need to minimize the frequency of events in which ice is disrupted by large changes in release volumes and river stage, which can flood or desiccate nursery backwaters and displace the young fish.

Valdez, R. A., B. R. Cowdell, and L. D. Lentsch. 1999. Overwinter survival of age-0 Colorado pikeminnow in the Green River, Utah, 1987–1995. Final Report of BIO/WEST, Inc. to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project FG-10)

Catch rates of age-0 Colorado pikeminnow *(Ptychocheilus lucius)* were compared between fall (September–October) and spring (March–April) sampling periods as indices of overwinter survival in two reaches of the Green River, Utah. Overwinter survival indices were determined for the year classes 1987–95 for Reach 3 (Colorado River confluence upstream to Green River, Utah; 193 km) and for the year classes 1989–94 for Reach 4 (Sand Wash upstream to Split Mountain, Utah; 169 km). Average indices were 54% (23–100%) and 51% (29–96%), respectively.

Overwinter survival indices for Reach 3 were compared to total length of fish in fall, flow variability, river temperature, average backwater depth, and fall densities of non-native fishes. No clear relationships were revealed for fish length, river temperature, or densities of non-native fishes. Lower survival was demonstrated for higher fluctuating river flows, and significantly higher survival was related to backwater depth. Backwaters with mean depths of > 120 cm showed the highest overwinter survival index of 85%, compared to only 18% for backwaters with mean depth of <30 cm. These findings show that backwaters deepened by appropriate antecedent flows provide greater resilience to inundation and desiccation as a result of fluctuating releases from Flaming Gorge Dam.

We noted that sampling in spring was preceded in all years by early runoff spikes from low elevation snowmelt and river ice breakup, and hypothesize that much of the decrease in densities of age-0 Colorado pikeminnow in nursery backwaters is related to a natural survival strategy of downstream dispersal. This hypothesis is supported by findings of highest densities of age-0 Colorado pikeminnow in the Lake Powell inflow immediately following these March spikes in 1993 and 1994.

These analyses show that interactions among variables affecting survival of age-0 Colorado pikeminnow are complex. Catch rate statistics collected in fall and spring may be of insufficient sensitivity to provide accurate and reliable estimates of fish density. This paper concludes that overwinter survival of age-0 Colorado pikeminnow must be considered as an important aspect in overall survival of fish to age of recruitment, but existing measures of fall and spring densities show high variability that is partly attributed to annual population variability as well as to sampling. We believe that understanding the fate of age-0 Colorado pikeminnow during the winter period is the key to determining cohort strength and recruitment to the adult portion of the population. It is important to understand and separate the effect of anthropogenic actions from natural life history strategies on long-term conservation of this species.

Wick, E. J. 1997. Physical processes and habitat critical to the endangered razorback sucker on the Green River, Utah. Doctoral Dissertation. Colorado State University, Fort Collins.

The last self sustaining, riverine population of razorback sucker occurs on the middle Green River. Since 1962, operations at Flaming Gorge Dam have reduced flow variability, reduced duration of flood peak, and altered timing of spring flows. These flow changes modified fluvial processes related to sediment movement and deposition at the primary spawning site and connectivity to downstream floodplain nursery habitat which are critical to razorback sucker reproductive success.

Physical and biological studies related to the early life history of the razorback sucker were conducted from 1992 to 1996. The primary spawning site of the middle Green River population is located along the right side of an alluvial channel around a large island at river kilometer 500. Physical evaluation of the primary spawning bar was conducted using repeated cross sectional surveys and one dimensional HEC-2 and HEC-6 modeling. This analysis found this site to be influenced by the backwater effect of a constriction at the downstream end of the island complex. This backwater condition causes reduced velocity and reduced water surface-slope in the spawning channel as flows rise during spring runoff.

HEC-6 analysis was conducted using averaged post-darn USGS suspended load data, 1996 USGS bedload data, and 1993 bed material samples. The magnitude and pattern of model-simulated deposition and scour were very similar to empirical measurements in 1993 and 1996. Major sedimentation at the site (HEC-6 output) began at 325 m^3/s and ultimately resulted in an average of 0.6 meters deposition of sand at peak flows approaching 650 m^3/s. Model simulation and physical measurements at the site showed that sediment was scoured off the bar during August as declining flows resulted in increased slope and velocity in the spawning channel.

Bed material analysis of sand deposition at the spawning channel indicates that sand between 0.5–1.0 mm in diameter predominates. Sediment transport samples collected in 1996 indicate that this size material moves mostly as bedload as flows approach 425 m^3/s. Scour chain analysis in an overflow channel immediately above the spawning area indicates that sand sized material is supplied to the spawning channel on the rising limb as flows exceed 325 m^3/s.

From an evolutionary perspective, based on large percentage of ripe adult fish using the site, age structure of the adult population, and recruitment success patterns since closure of Flaming Gorge, it is not logical that the primary spawning bar at river kilometer 500 would be a consistently poor producer of larvae during high flow years. Historical recruitment success appears tied to years when high flow conditions provided river connectivity to floodplain habitat. Physical process and biological response data collected during this study showed that spawning conditions remain suitable and numbers of razorback larvae are higher at reference collection sites below the spawning bar when Green River discharges at Jensen remain below present effective discharge of 325 m^3/s. Sedimentation begins to impact the site as flows exceed 325 m^3/s and numbers of razorback larvae caught at reference collection sites are considerably lower than in years when flows do not exceed this level. Razorback adults must spawn and resultant larvae hatch and emerge from cobble substrates prior to deposition of sand which can bury and/or suffocate the larvae.

It is hypothesized that reductions in peak discharges on the Green River below Flaming Gorge Dam have resulted in sediment being stored at low elevations in the channel bed and river margins due to a lower range of peak flows. This has led to conditions where available sediment is now transported at a narrower range of lower peak flow levels. Effective discharge levels on the middle Green River have been reduced from 580 m^3/s during the pre-dam period to 325 m^3/s during the post-dam period (1964-1981).

Higher peak flows are needed to redistribute sediment stored in river beds and margins to higher elevations on river margins so that less sediment will be available for transport on the rising limb in subsequent years. It is recommended that flow releases following high flow management years be managed to remain below newly established surface deposits and mimic natural inflow patterns above Flaming Gorge Dam. Premature high spring releases should be avoided by anticipating safe reservoir levels further in advance to accommodate experimental release patterns. These experimental flow release patterns need to be tested using an adaptive management approach utilizing channel monitoring programs and standardized larval fish monitoring programs to evaluate anticipated physical and biological responses.

Williams, G. P., D. Tomasko, H. E. Cho, and S. C. L. Yin. 1995. Effects of Flaming Gorge Dam hydropower operations on sediment transport in the Browns Park reach of the Green River, Utah and Colorado. Environmental Assessment Division, Argonne National Laboratory, Argonne, Illinois. Report ANL/EAD/TM-6.

Three methods for comparing sediment transport were applied to four proposed hydropower operational scenarios under study for Flaming Gorge Dam on the Green River in Utah. These methods were effective discharge, equilibrium potential, and cumulative sediment load with flow exceedance plots. Sediment loads transported by the Green River in the Browns Park reach were calculated with the Engelund-Hansen equation for three historical water years and four hydropower operational scenarios. A model based on the Engelund-Hansen equations was developed using site-specific information and validated by comparing predictions for a moderate water year with measured historical values. The three methods were used to assess the impacts of hydropower operational scenarios on sediment resources. The cumulative sediment load method provided the most useful information for impact evaluation. Effective discharge was not a useful tool because of the limited number of discrete flows associated with synthetic hydrographs for the hydropower operational scenarios. The equilibrium potential method was relatively insensitive to the variations in operating conditions, rendering it comparatively ineffective for impact evaluation.

Wolz, E. R., and D. K. Shiozawa. 1995. Soft sediment benthic macroinvertebrate communities of the Green River at the Ouray National Wildlife Refuge, Uintah County, Utah. Great Basin Naturalist 55:213–224.

Benthic macroinvertebrates from four habitat types (river channel, ephemeral side channel, river backwater, and seasonally inundated wetland) were examined from the Green River at the Ouray National Wildlife Refuge, Uintah County, UT, June–August 1991. Four major taxa (Nematoda, Oligochaeta, Diptera, Ceratopogonidae, and Chironomidae) were quantified. Cluster analysis of densities showed that habitat types with comparable flow conditions were the most similar. Highest to lowest overall benthic invertebrate densities of the four habitats were as follows: ephemeral side channel, river backwater, seasonally inundated wetland, and river channel. Nematodes were the most abundant taxon in all habitat types and sample dates except the August sample of the river channel and river backwater and the July sample of the seasonally inundated wetland.

Wyodoski, R. S., and E. J. Wick. 1998. Ecological value of floodplain habitats to razorback suckers in the upper Colorado River basin. Final Report of U.S. Fish and Wildlife Service and U.S. National Park Service to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. ***Abstract excerpted from Executive Summary***

This report is intended as a reference document for persons working on habitat enhancement projects related to the Recovery Implementation Program for Endangered Fishes in the

Upper Colorado River Basin (Recovery Program). It summarizes the published literature on the ecological value of floodplains to riverine fish communities and relates this literature to reports that have been developed through the Recovery Program and management endeavors in the Lower Colorado River Basin. The report emphasizes the need for concurrent integration of all Recovery Program elements, especially habitat development and maintenance, management of nonnative fishes and sport fishing, and captive propagation.

Yin, S. C. L., J. J. McCoy, S. C. Palmer, and H. E. Cho. 1995. Effects of Flaming Gorge Dam hydropower operations on flow and stage in the Green River, Utah and Colorado. Environmental Assessment Division, Argonne National Laboratory, Argonne, Illinois. Report ANL/EAD/TM-4.

This report presents the development of Flaming Gorge Reservoir release patterns and resulting downstream flows and stages for four potential hydropower operational scenarios. The release patterns were developed for three representative hydrologic years: moderate, dry, and wet. Computer models were used to estimate flows and stages in the Green River resulting from these release patterns for the moderate water year. The four hydropower operational scenarios for Flaming Gorge Dam were year-round high fluctuating flows, seasonally adjusted high fluctuating flows, seasonally adjusted moderate fluctuating flows, and seasonally adjusted steady flows. The year-round high fluctuating flow scenario assumes that the monthly total reservoir releases would be the same as historical releases. The remaining seasonally adjusted flow scenarios would comply with the 1992 Biological Opinion of the U.S. Fish and Wildlife Service, which requires high flows in the spring and limited hourly fluctuations, especially in summer and autumn releases, to protect endangered fish. Within one year, the maximum daily river stage fluctuations resulting from hydropower operations under the seasonally adjusted high fluctuating flow scenario would be similar to the maximum daily fluctuations under the year-round high fluctuating flow scenario. However, reduced or no fluctuations would occur in some time periods under the former scenario. The maximum daily river stage fluctuations under the seasonally adjusted moderate fluctuating flow scenario would be about half of those under the seasonally adjusted high fluctuating flow scenario.

APPENDIX C:

LISTS OF WORKSHOP PARTICIPANTS

This appendix provides lists of Flaming Gorge Technical Integration Team members, principal investigators of the Flaming Gorge Research Group, and other interested persons who participated in workshops to discuss research findings, formulate preliminary flow and temperature recommendations, and review preliminary drafts of this synthesis report.

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