Prepared in cooperation with Canyonlands National Park

The Effects of Requested Flows for Native Fish on Sediment Dynamics, Geomorphology, and Riparian Vegetation for the Green River in Canyonlands National Park, Utah

Open-File Report 2022–1019

U.S. Department of the Interior
U.S. Geological Survey

Cover. Photograph of the Green River in Canyonlands National Park, Utah. View is looking upstream in Labyrinth Canyon. U.S. Geological Survey photograph taken March 18, 2021 by Paul Grams.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

Abbreviations

FWS U.S. Fish and Wildlife Service

Reclamation Bureau of Reclamation

USGS U.S. Geological Survey

The Effects of Requested Flows for Native Fish on Sediment Dynamics, Geomorphology, and Riparian Vegetation for the Green River in Canyonlands National Park, Utah

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Abstract

Releases of water from Flaming Gorge Dam together with climate-related variations in runoff determine the streamflow regime of the Green River, which affects the physical characteristics of the channel and riparian ecosystem of the Green River corridor in Canyonlands National Park. The dam has decreased peak streamflows and raised base streamflows, resulting in vegetation encroachment and channel narrowing and simplification, which could be detrimental to endangered fish habitats over time. Operations of Flaming Gorge Dam are in part determined by flow recommendations provided by the Upper Colorado River Basin Endangered Fish Recovery Program that are designed to benefit native fish and disadvantage nonnative fish. These recommendations alone may not be sufficient to prevent channel narrowing and simplification. Increases in base flows may contribute to channel narrowing and simplification by increasing the water available to riparian vegetation and reducing the water volume available for increasing peak-flow magnitude or duration This report describes how proposed revisions to these flow recommendations would affect the physical characteristics of the Green River corridor in Canyonlands National Park, with a focus on riparian vegetation and channel width.

Hydrologic conditions for the Green River downstream from Flaming Gorge Dam are classified by the U.S. Department of the Interior Bureau of Reclamation as dry, moderately dry, average, moderately wet, or wet. The flow recommendations for peak-flow magnitude and duration in wet years are consistent with geomorphic objectives and historical post-dam flows. In moderately wet years, although the recommended peaks may be sufficient to prevent narrowing over the short term, these peaks are lower than historical post-dam peak flows for moderately wet years and could therefore allow reduction in the occasional large peaks necessary to maintain sediment mobility and channel complexity. For average and drier years, the recommendations allow, but do not require, peak-flow magnitude and durations that are likely to achieve geomorphic objectives.

Introduction

The physical characteristics of the channel and riparian ecosystem of the Green River corridor in Canyonlands National Park are strongly affected by the streamflow regime of the Green River. The streamflow regime is determined by runoff from high elevation parts of the drainage basin and by the reservoir releases from Flaming Gorge Dam, 580 kilometers (km) upstream from the park boundary. Flaming Gorge Dam is operated to meet water delivery requirements, resource management objectives (Department of the Interior, 2006), and to generate electricity. A major resource management objective is recovery of threatened and endangered native fish in the Green and Yampa Rivers (Minckley and others, 1986; Stanford and Ward, 1986). As part of recovery efforts, the Fish and Wildlife Service (FWS) has designated a section of the Green River, from the Yampa River confluence to the Colorado River confluence, as critical habitat for these threatened and endangered fish (Maddux and others, 1993). Accordingly, the Upper Colorado River Endangered Fish Recovery Program (hereafter, "Recovery Program") of the FWS and cooperators (https://coloradoriverrecovery.org/) has conducted studies on native fish populations, habitat, and ecology and developed recommendations for flow regimes designed to benefit native fish populations (LaGory and others, 2019).

The purpose of this report is to describe how the streamflow recommendations of Muth and others (2000) and the revised recommendations of LaGory and others (2019) for native fishes may affect the river channel morphology, sediment dynamics, and riparian vegetation of the Green River in Canyonlands National Park. Although the recommendations made in those reports are designed to benefit native fish, they include many objectives that are related to the creation and maintenance of fish habitat and encompass all aspects of the annual flow regime, including peak-flow magnitude, peak-flow duration, peak-flow timing, and base flows.

Muth and others (2000) and LaGory and others (2019) provide separate flow recommendations for each of the three segments of the Green River between Flaming Gorge Dam and the confluence of the Green and Colorado River in Canyonlands National Park, termed reaches 1–3 (fig. 1). Although the recommendations for each segment are separate, they are inherently related because the only mechanism to control streamflow for any segment is adjusting reservoir releases from Flaming Gorge Dam. Therefore, the recommendations for the segment that includes Canyonlands National Park (reach 3) are specified to be consistent with the recommendations for the upstream segments, because priorities for those segments typically determine releases from Flaming Gorge Dam. The LaGory and others (2019) flow recommendations are driven by priority objectives for the two species of native fish (Colorado pikeminnow and Razorback sucker) that are of greatest concern, briefly summarized below.

Colorado pikeminnow (*Ptychocheilus lucius*) utilize shoreline habitats that include side channels and bank irregularities created by dynamic, non-cohesive sand bars (LaGory and others, 2019). Spring peak flows that vary in annual magnitude are therefore recommended (LaGory and others, 2019) because those flows are responsible for constructing and reshaping these habitats. Preventing loss of these habitats, which can occur by expansion of riparian vegetation and channel narrowing, is also an objective.

Young-of-the-year (less than 1 year) Colorado pikeminnow utilize shoreline habitats including backwaters—regions of low velocity separated from the main channel by a sandbar with an entrance at one end of the sandbar (Grippo and others, 2017; Hamada and others, 2017). Other shoreline habitats include talus-covered and vegetated banks. Although the fish are known to utilize backwaters, it is not known whether backwater habitat is a limitation to pikeminnow success. The LaGory and others (2019) flow recommendations for summer base flows are based primarily on the conclusions of Bestgen and Hill (2016) that pikeminnow density in backwaters was greater in years with base flows between 1,700 and 3,000 cubic feet per second (ft^3/s).

The recommendations also consider the Razorback sucker (*Xyrauchen texanus*), which spawn in the spring upstream from Canyonlands National Park in reach 2 (fig. 1). The larvae hatch and drift downstream before they are able to swim. Inundated floodplains and wetlands are likely the best habitat for larval growth and survival (Lagory and others, 2019). Therefore, many of the objectives for peak-flow magnitude and duration are designed to achieve floodplain and wetland inundation and match those conditions with the timing of larval drift.

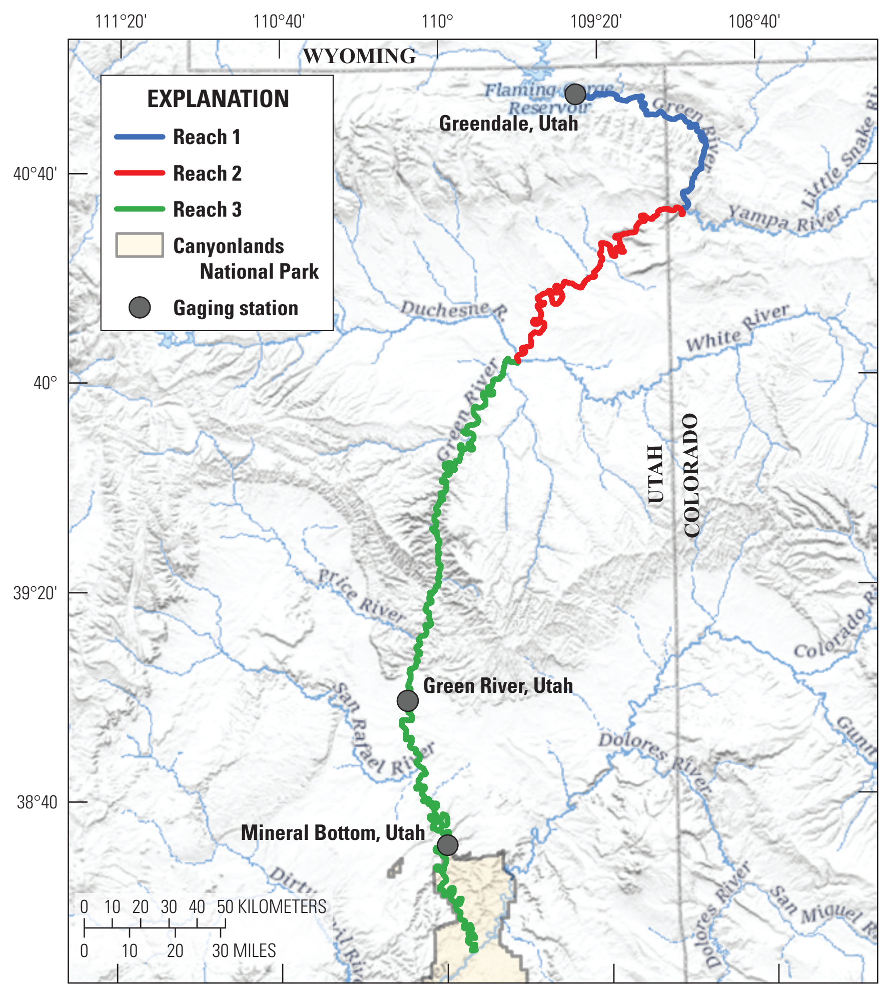

Figure 1. Map of the Green River Basin adapted from Muth and others (2000) showing the flow-recommendation reaches used in LaGory and others (2019) and Muth and others (2000).

Nonnative fish compete with and prey upon several species of native fish, including the Colorado pikeminnow and Razorback sucker, and are likely a substantial impediment to native fish recovery (LaGory and others, 2019). Some flow objectives, such as late spring or summer short-duration flow spikes, are designed to disadvantage nonnative fish, specifically smallmouth bass (*Micropterus dolomieu*).

Flow Variability, Channel Narrowing, and Riparian Vegetation

Although plants require water for survival, high flows kill plants by erosion and extended inundation (Sigafoos, 1964; Gill, 1970; Auble and Scott, 1998), and low flows kill plants through desiccation (Auble and Scott, 1998). Unregulated or mostly free-flowing rivers of western North America typically have large inter- and intra-annual flow variability, resulting in rapid channel movement, complex multi-thread channels and sparse vegetation near the channels (Naiman and others, 2005; Bagstad and others, 2006; Friedman, 2018). Where geology, precipitation patterns, or flow regulation reduce flow variability, the result is a narrow, stable channel bordered by dense vegetation with little opportunity for establishment of disturbance-dependent species (O'Connor and Grant, 2003).

Decreases in peak flows and increases in base flows result in a narrower river channel, as perennial terrestrial vegetation becomes established and traps sediment on the channel bed, side channels, and banks. Thus, flow regulation has caused channel narrowing and simplification and encroachment of riparian woody and herbaceous vegetation in western North America in general (Williams and Wolman, 1984; Johnson, 1994; Mortenson and Weisberg, 2010) and the Colorado River system in particular (Allred and Schmidt, 1999; Merritt and Cooper, 2000; Cooper and others, 2003; Webb and others, 2011; Manners and others, 2014; Sankey and others, 2015). Along the flow-regulated Green River, decreases in peak flows have allowed establishment of pioneer riparian species, especially invasive tamarisk (*Tamarix spp.*), on exposed bars, resulting in channel narrowing and simplification and development of a broad tamarisk forest (Grams and Schmidt, 2002, 2005; Grippo and others, 2017; Dean and others, 2020; Grams and others, 2020; Walker and others, 2020). Between Flaming Gorge Dam and the Yampa River confluence, this process has decreased channel width by 10–30 percent (Grams and Schmidt, 2005). In Canyonlands National Park—downstream from the confluence with the less flow-regulated Yampa River and other tributaries—the channel of the Green River has narrowed by this process by ~12 percent between 1940 and 2014 (Walker and others, 2020).

Seedlings of riparian plants are susceptible to removal in subsequent years by desiccation during low flows or by inundation and disturbance during high flows. The elevation of plant establishment in the first year affects the susceptibility to desiccation or inundation in the second year. Seedlings established high on the bank in a high-flow year may die from desiccation if flow is much lower in year two. Conversely, seedlings established low on the bank in a low-flow year will likely die from inundation or erosion if the peak is larger in year two. Flow variability between years therefore helps to maintain a wide, complex channel and sparsely vegetated floodplain. In contrast, sequences of years with similar flows promote establishment of woody plants, including invasive tamarisk (Sponseller and others, 2013). Vegetation encroachment is especially severe during multiple successive years of below-average peak flows (Grams and others, 2020; Walker and others, 2020). Once established, the vegetation promotes sediment deposition and channel narrowing and simplification and is less susceptible to scour by all but extreme floods (Zong and Nepf, 2010; Le Bouteiller and Venditti, 2014; Diehl and others, 2017; Butterfield and others, 2020).

Hydrology and Hydrologic Condition

Streamflow of the Green River in Canyonlands is partly determined by regulation at Flaming Gorge Dam and partly determined by the largely unregulated flows from the Yampa River and other tributaries. Using a change-point analysis (Pettitt, 1979), Walker and others (2020) did not identify a long-term trend in annual runoff at the U.S. Geological Survey (USGS) Green River at Green River, Utah, 09315000 gaging station (fig. 2) between 1930 and 2017. However, climate-driven periods of below and above average streamflow occurred within that period, and the mean annual flow between 2000 and 2018 was significantly lower than the mean annual flow from 1963 to 1999 (fig. 3). Although flow regulation reduced the magnitude of peak flows (the 2-year recurrence flood) by 23 percent from the pre-Flaming Gorge Dam period to the post-Flaming Gorge Dam period (Walker and others, 2020) (fig. 3), the average peak flow has not changed since 1963. To evaluate how these changes in mean annual flow and peak flow affected the typical distribution of daily flows, we computed the average hydrograph for three time periods between 1930 and 2018 for the Green River at Green River, Utah. The 1930–1962 period is the period before Flaming Gorge Dam was completed, herein the "pre-dam period." The "post-dam period" is 1963–2018, which we subdivide into two periods based on the onset of drought conditions in 2000. Our computations showed a decrease in peak flows and increase in base flows for the 1963–1999 period relative to the pre-dam period (fig. 4). For the 2000–2018 period, peak flows continued to decrease and there was a decrease in base flows relative to the 1963–1999 period that resulted in base flows that were similar to base flows in the pre-dam period.

LaGory and others (2019) follow Muth and others (2000) in specifying flow recommendations that vary depending on annual runoff volume. Runoff is categorized by hydrologic condition, which is classified each year by the Bureau of Reclamation (hereafter referred to as Reclamation) as

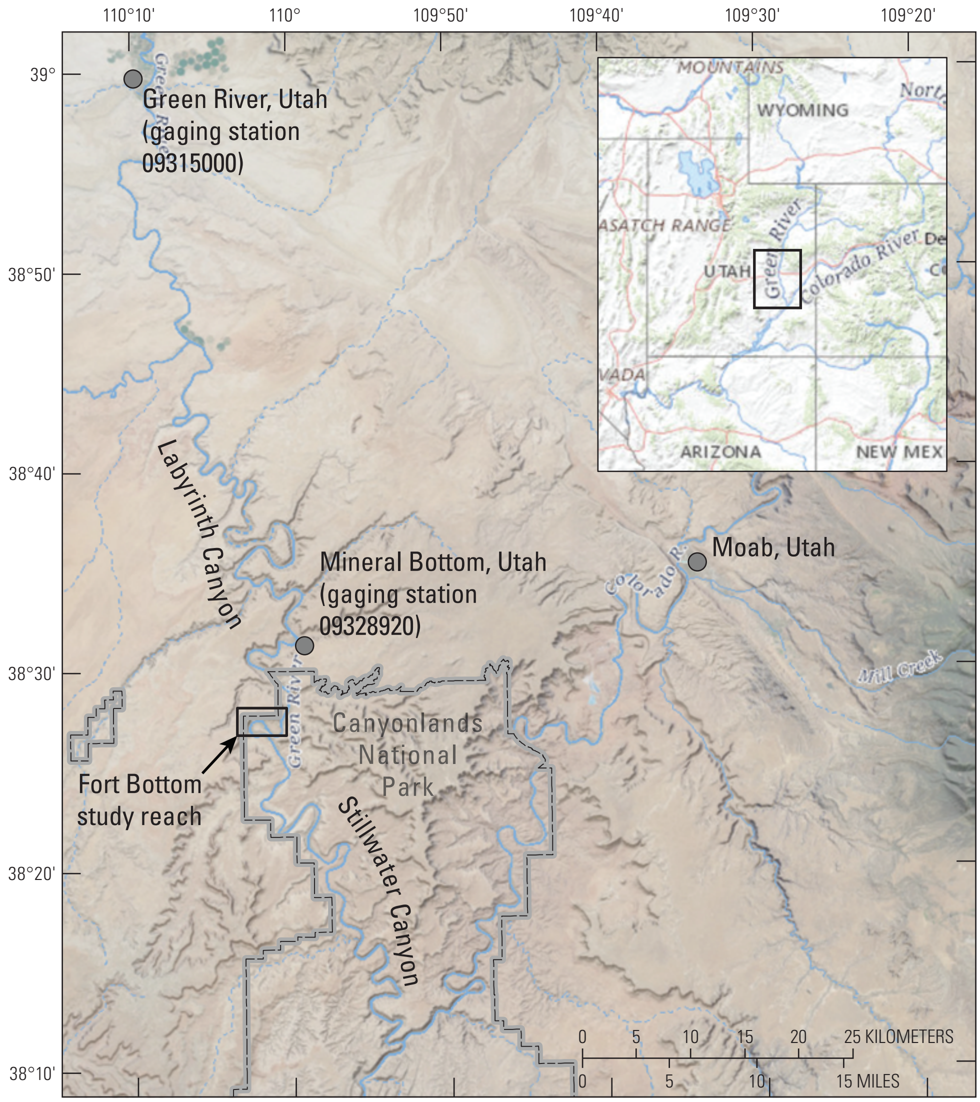

Figure 2. Map of the northern part of Canyonlands National Park, showing stream gaging stations and the 5-kilometer Fort Bottom study reach (solid black box). Streamflow direction is from top to bottom.

dry, moderately dry, average, moderately wet, or wet. The classification is based on comparing runoff volume forecasts generated on May 1 with annual exceedance of historic unregulated April–July inflow to Flaming Gorge Reservoir from 1963 to the year before the current year. The intended frequencies of occurrence for each hydrologic condition are 10 percent wet, 20 percent moderately wet, 40 percent average, 20 percent moderately dry, and 10 percent dry. Unregulated inflow is actual inflow corrected for effects of storage and evaporation at Fontenelle Reservoir.

The effect of upstream flow regulation on the distribution of daily flows at Green River, Utah varies depending on the hydrologic condition (see appendix 1 for description of how the hydrologic condition was determined for years before 1963). In wet and moderately wet years, the peak-flow magnitude and duration were very similar before and after installation of the Flaming Gorge Dam (fig. 4); however, flows in the September through March base flow period were much higher after dam installation. In average, moderately dry, and dry years, the peak flows tended to be lower and, for average and moderately dry years, shorter duration, after dam installation. In average years, base flows were higher after dam installation, but not by as much as in the wetter years.

Assessment of flow recommendations

For each flow recommendation made by the Recovery Program in LaGory and others (2019), we describe the characteristics of the recommendation and the physical processes associated with that aspect of the flow regime, and then follow with a discussion of the implications for that flow recommendation on sediment dynamics, channel morphology, and riparian vegetation. LaGory and others (2019) describe the recommendations in greater detail and summarize the recommendations in tables 5–6 of that report.

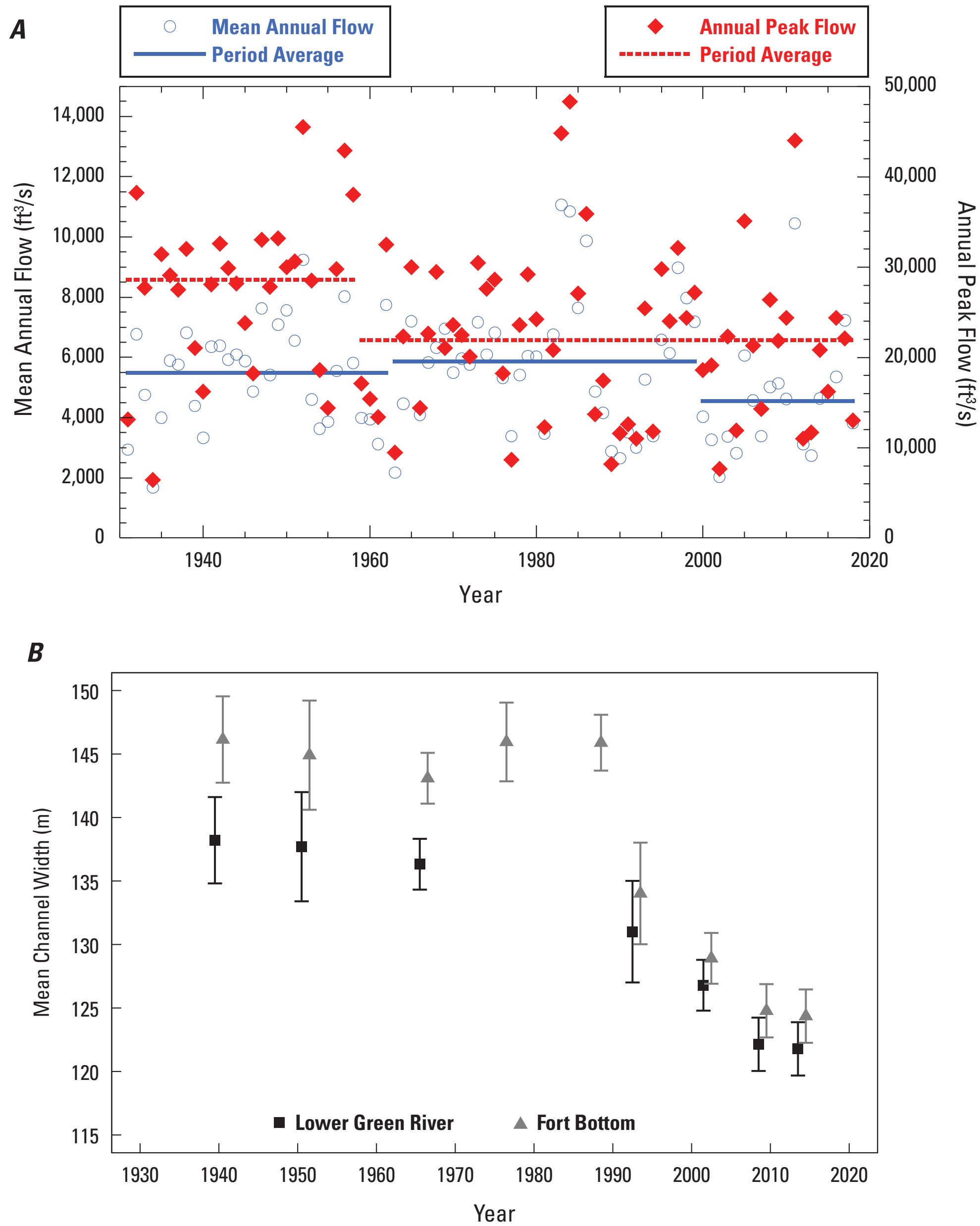

Figure 3. Plots of flow and channel width of the Green River, Utah. *A*, mean annual flow and annual peak flow for the Green River at Green River, Utah, for 1931–2018. Mean annual flow is computed as the mean for each year among the published U.S. Gelogical Survey record of daily mean discharge. The mean annual flow for the 2000–2018 period (4,540 cubic feet per second [ft^3/s]) was significantly lower than the mean annual flow for the 1963–1999 period (5,860 ft^3/s) (Student's t-test p = 0.025) and for the entire 1931–1999 period (5,690 ft^3/s) (Student's t-test p = 0.029). The mean annual flow for the 1963–1999 period was not significantly different from the 1931–1962 period. The annual peak flow for the 1959–2018 period (21,900 ft^3/s) was significantly lower than for the 1931–1958 period (28,600 ft^3/s) (Walker and others, 2020). *B*, time series showing mean channel width based on analysis of aerial imagery for 61 kilometers (km) of the Green River in Canyonlands National Park (black squares) and the 15-km Fort Bottom reach (gray triangles) with uncertainty based on image distortion and measurement error (from Walker and others, 2020). m, meters.

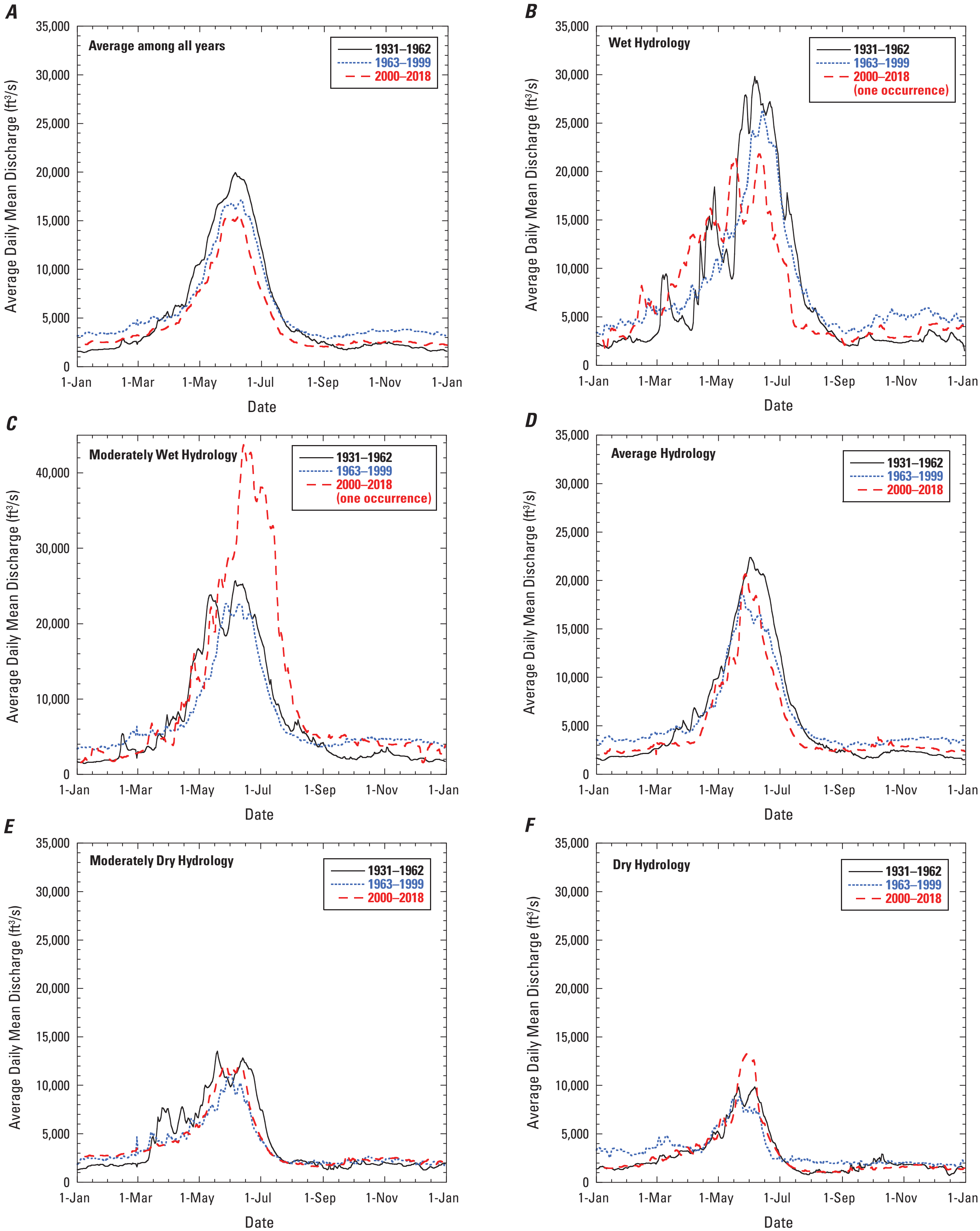

Figure 4. Plots of average daily mean discharge of the Green River at Green River, Utah. These values were calculated by averaging the daily mean discharge for each day in a common year among those years classified into each of the five hydrologic conditions in the three indicated periods. The method for estimating hydrologic condition for 1931–1992 is described in appendix 1. Hydrologic condition for 1993–2018 is from LaGory and others (2019).

Peak-flow magnitude

Description of Recovery Program recommendation for peak-flow magnitude

LaGory and others (2019) recommend that peak-flow magnitude range from 8,300 ft^3/s to greater than 39,000 ft^3/s, depending on the hydrologic condition. We compared the recommended peak-flow magnitudes with the computed recurrence interval (expressed as exceedance probability) based on the record of peak flows from 1963 to 2017 (table 1). In this analysis, we compared the magnitude of the recommended peak flows to the magnitude of the observed peak flows for each hydrologic condition. For example, in the case of a wet year the recommended peak flow of 39,000 ft^3/s has an exceedance probability of 5 percent, which is the midpoint of the range of exceedance probabilities that define the wet condition. The recommended peak is therefore consistent with the hydrologic condition. For dry years, the recommended flows are also generally consistent with the hydrologic condition. For moderately wet and moderately dry years, the recommended peak flows are low relative to the hydrologic condition because the exceedance probabilities for the recommened peak flows are high. The recommended flows are slightly high for the wetter half of average years and low for the drier half of average years. Thus, the recommendations of LaGory and others (2019) could have the result of skewing peak flows to be lower than the hydrologic condition for some years. During a period of multiple consecutive years with annual runoff volume below the 50-percent exceedance, the recommended peak would be low for the hydrologic condition in most years and would not exceed 14,000 ft^3/s, the 81-percent exceedance. In other words, the recommendations could allow reduced peak flows relative to the hydrologic condition during multi-year droughts.

Physical and biological processes related to peak-flow magnitude

The role of peak flows in shaping channel geometry has been addressed in many studies conducted throughout the Green River system since the 1970s (for example, Graf, 1978; Everitt, 1979; Andrews, 1986; Lyons and others, 1994; Allred and Schmidt, 1999; Grams and Schmidt, 2002, 2005; Birken and Cooper, 2006; Topping and others, 2018; Dean and others, 2020; Grams and others, 2020; Walker and others, 2020). Although some studies identified invasive tamarisk as the driving force of channel narrowing on the Green River (Graf, 1978; Birken and Cooper, 2006), most studies have concluded that flood magnitude reduction has been the primary driver of the observed channel narrowing that has occurred throughout all segments of the Green River from Flaming Gorge Dam to the confluence with the Colorado River in Canyonlands National Park (Everitt, 1979; Andrews, 1986; Lyons and others, 1994; Allred and Schmidt, 1999; Grams and Schmidt, 2002, 2005; Dean and others, 2020; Grams and others, 2020; Walker and others, 2020;). The most recent studies (Grams and others, 2020; Walker and others, 2020) specifically identified periods of exceptionally low flood magnitude as the direct cause for channel narrowing. Periods of low peak flow allow recruitment and establishment of riparian vegetation, including tamarisk, which facilitates floodplain growth and channel narrowing (Manners and others, 2014; Friedman, 2018; Walker and others, 2020). If subsequent peak flows fail to scour the new vegetation, the vegetation likely promotes floodplain accretion by increasing floodplain surface roughness and thereby increasing deposition rates (Griffin and others, 2005; Vargas-Luna and others, 2019). In reviewing the timing of channel narrowing relative to average flood magnitude, Grams and others (2020) found that the highest channel narrowing rate occurred during periods when the 5-year average peak flow was less than 60 percent of the long-term

Table 1. Description of peak-flow magnitude recommendations for reach 3

[ft^3/s, cubic feet per second]

Hydrologic condition	Exceedance range for condition based on projected annual runoff volume	Recommended peak (ft^3/s)[1]	Exceedance probability of recommendation[2]	Description of recommendation[3]
Wet	0–10%	39,000	5%	Consistent with hydrologic condition
Moderately wet	10–30%	24,000	32%	Low for hydrologic condition
Average	30–70%	14,000/22,000	81%/42%	Either low or slightly high for hydrologic condition
Moderately dry	70–90%	8,300	94%	Very low for hydrologic condition
Dry	90–100%	8,300	94%	Consistent with hydrologic condition

[1]From table 5–6 in LaGory and others (2019). For each condition except average, the recommendation is for flows to be greater than or equal to the listed value. For average years, the recommendation is to meet the target in 50 percent of average years and rely on the recommendation for reach 2 in other average years. For reach 2, the minimum recommended peak discharge for average years is 14,000 ft^3/s.

[2]Exceedance probability based on Log-Pearson Type III distribution of annual peak flows for 1963–2017 at the Green River at Green River, Utah, 09315000 gaging station.

[3]Description of the degree to which the recommended peak flow is consistent with the associated 1963–2017 hydrologic condition.

average peak flow of 22,000 ft^3/s (fig. 3). For example, in the period between 1988 and 1993—the period of most rapid channel narrowing on the Green River in Canyonlands National Park (Walker and others, 2020)—the 5-year average peak flow was less than 13,000 ft^3/s for two consecutive years (1988 and 1989). Annual peak flow was less than 13,000 ft^3/s in 1989–1992, and 1994. These periods of exceptionally low peak flow represent the combined effects of streamflow regulation by Flaming Gorge Dam and climatically driven low runoff, caused by low precipitation and(or) increased temperature (Udall and Overpeck, 2017). Aerial photographs show that rapid channel narrowing continued on the lower Green River (downstream from Green River, Utah) until August 2009 (Walker and others, 2020), which brackets another low flow period (2000–2004) where the 5-year average peak flow was 15,900 ft^3/s, which is less than 75 percent of the long-term average peak flow.

Because decreases in average peak-flow magnitude have caused channel narrowing in the past (Andrews, 1986; Allred and Schmidt, 1999; Grams and Schmidt, 2002; Walker and others, 2020), further decreases in peak-flow magnitude can be expected to result in additional channel narrowing and simplification. Additional channel narrowing is most likely to occur during periods of ~3 or more years with consistently low annual floods. Although the precise reduction in peak-flow magnitude required to cause channel narrowing is difficult to quantify, previous studies show that periods with average peak flow of about 60 percent of the long-term average peak flow have resulted in channel narrowing (Walker and others, 2020). Based on observations made during the 2017 peak flow, and associated streamflow modeling for a 5-km study reach near Fort Bottom in Canyonlands National Park (fig. 2), Grams and others (2020) concluded that peak flows of average magnitude (~22,000 ft^3/s) transported bed sediment in suspension throughout the main channel and secondary channels, creating transport conditions likely sufficient to maintain channel width and complexity. Furthermore, they found that peak flows less than about 75 percent of the average flood, or 16,000 ft^3/s, were insufficient to transport bed sediment in suspension in all regions of the multi-thread channel segment. Together, these findings indicate that periods of 3 or more years with average peak flow in the range of 60–75 percent of the long-term average peak flow create risk for additional channel narrowing.

Although the inflow to Flaming Gorge Reservoir is partly regulated by the upstream Fontenelle Dam, insight into unregulated Green River flows can be obtained by analysis of the mean annual natural flow record developed by Reclamation as an estimate of flows that would exist in the absence of consumptive uses and losses (Reclamation, 2020). The Reclamation record of April–July natural inflow to Flaming Gorge Reservoir during 1963–2020 (58 years) indicates that periods of 3 or more years with flow below the median have increased in frequency over time. Although such flows did not occur during the first half of this record, from 1963 to 1986 (24 years), they did occur during 1987–1994, 2000–2004, and 2006–2008. The increasing frequency of droughts along the Green River in recent decades is consistent with the increased frequency of extended droughts and high-flow periods observed on the Yampa River (Manners and others 2014). Increased drought frequency is also consistent with the assessment by the U.S. Department of the Interior (2012) that droughts lasting five or more years may occur 50 percent of the time over the next 50 years in the Colorado River Basin.

Both peak-flow magnitude and duration are likely important in preventing channel narrowing (Dean and others, 2020). Although channel narrowing and simplification can be prevented in the short term by peak flows of 22,000 ft^3/s or greater, occasional peak flows larger than the 2-year recurrence flood are likely necessary to maintain a dynamic, complex channel. These flows enable general mobilization of gravel and cobble in canyon reaches and remobilization of tributary fans (Manners and others, 2014). Flows greater than about 22,000 ft^3/s also remove established riparian vegetation from secondary channels and floodplain areas, promoting long-term channel complexity and mobility (Friedman, 2018). The importance of longer duration floods in preventing channel narrowing is described in the “peak-flow duration” section.

Implications of Recovery Program recommendations for peak-flow magnitude

In wet, moderately wet, and the wetter half of average years, the Recovery Program recommended that the peak flows needed to maintain channel width and complexity are 22,000 ft^3/s or greater, although the recommended peak magnitude for moderately wet years (24,000 ft^3/s) is low relative to post-dam peaks for such years (table 1). Thus, the recommended peak magnitude for moderately wet years could decrease the magnitude of occasional large peak flows. These large peak flows have been observed to play important roles in promoting channel complexity and sediment mobility (Manners and others, 2014; Friedman, 2018). More importantly, the recommended peak magnitudes for moderately dry years and the drier half of average years are very low compared to post-dam flows. Low peak flow periods of 3–5 years have been associated with channel narrowing along the lower Green River in the past (Walker and others, 2020), and the Recovery Program recommendations could allow such narrowing in the future. As a multi-year drought progresses, there is an increased need for relatively high spring peak flows that are near the magnitude of the 2-year recurrence flood to forestall narrowing. A high peak flow could be accomplished by timing the peak flow release from Flaming Gorge Dam to coincide with the peak on the Yampa River as suggested by LaGory and others (2019).

Peak-flow duration

Description of Recovery Program recommendation for peak-flow duration

LaGory and others (2019) recommend peak-flow durations from 2 days to 4 weeks or more in dry and moderately dry years and that these flows should be maintained as long as possible in average, moderately wet, or wet years, ideally lasting 2 weeks or more. These recommendations are generally less than the earlier recommendations of Muth and others (2000), as LaGory and others 2019 states: “recognizing limitations on the ability to meet specific targets based on reservoir inflow, restrictions on spillway use, and Yampa River flow runoff patterns”. The recommendations are generally much lower than observed peak-flow durations during the 1993–2015 period, except for wet years, which did not occur between 1993 and 2015 (table 2). During moderately dry and dry years, observed peak-flow durations generally exceeded the recommended durations by about 3 weeks.

Physical and biological processes related to peak-flow duration

The importance of peak-flow duration in affecting geomorphic processes has received far less attention than peak-flow magnitude. However, recent studies have identified that changes in suspended sand concentration and grain size occur during snowmelt floods in the Green River in Canyonlands National Park (Dean and others, 2020) and that these changes likely have important implications for sediment transport and channel morphological adjustment (Grams and others, 2020). Dean and others (2020) showed that the concentration of sand in suspension decreased and the grain size of sand in suspension increased over the duration of the spring runoff period and that the effect was greater for longer duration floods, specifically for those floods with longer rising limbs. This behavior demonstrates that the supply of sand available for transport evolves during the spring runoff period and that less sand may be transported later in the runoff period (even at higher discharges) than is transported earlier in the runoff period. These patterns indicate greater depletion of the upstream sediment supply during spring snowmelt floods of longer duration. Greater depletion of the sediment supply necessarily indicates that erosion has occurred, thereby limiting processes of channel narrowing that require sediment deposition.

Grams and others (2020) connected this behavior with channel response in the Fort Bottom study reach (fig. 2) and found that parts of the channel that accumulated sediment during the rising limb of the 2017 snowmelt flood eroded later during the flood, with net scour occurring on the 5-km-long reach scale during this flood. This indicates that the decrease in sand concentrations as a result of depletion of the sand supply may translate to conditions that contribute to maintaining channel width and complexity. The data required to evaluate these conditions have only been collected at the USGS Green River at Mineral Bottom (fig. 2) near Canyonlands National Park 09328920 gaging station (hereafter referred to as Mineral Bottom) since 2014. Analyses of the continuous suspended sand data at this gaging station indicate that substantial coarsening of suspended sand and bed sand occurred over the long duration of the 2016 and 2017 snowmelt floods, when flows were above 8,300 ft^3/s for at least 60 days (table 3). The winnowing of bed sand associated with the coarsening of the suspended sand requires erosion of the bed sand; therefore, these data show that depletion of the sand supply requires erosional processes in the Green River.

Implications of Recovery Program recommendation for peak-flow duration

Recent studies have illustrated the importance of peak-flow duration in controlling sediment-transport processes and the role that peak-flow duration likely plays in maintaining channel form. Short-duration peak flows of any magnitude could create conditions where suspended-sediment concentrations remain high for the duration of the peak flow and result in greater deposition along the channel margins and on floodplains. Longer

Table 2. Comparison of peak-flow duration recommendations of LaGory and others (2019) for reach 3 with observations from 1993–2015 at the U.S. Geological Survey Green River at Green River, Utah gaging station.

[Recommended duration from tables 5 and 6 in LaGory and others (2019). In each case, the recommendation is for the minimum duration that flows should exceed the indicated value. The observed values are average number of days the target was met among all years within each hydrologic condition category between 1993 and 2015 as reported in tables 2–4 in LaGory and others (2019). NA, targets not specified in recommendation; --, no entry (reflects that no wet years were classified in 1993–2015).]

Hydrologic condition	Exceedance range for condition based on projected annual runoff volume	Peak-flow duration above 8,300 ft^3/s (days)		Peak-flow duration above 22,000 ft^3/s (days)		Peak-flow duration above 24,000 ft^3/s (days)	
		Recommended	Observed	Recommended	Observed	Recommended	Observed
Wet	0–10%	NA	--	28	--	14	--
Moderately wet	10–30%	NA	106	14	34	NA	26
Average	30–70%	NA	67	14*	17(1)*	NA	6
Moderately dry	70–90%	7	27	NA	1	NA	0
Dry	90–100%	2	23	NA	0	NA	0

*The recommendation is to meet this target in 1 of 4 average years. The observed values are for the average among the 4 average years with the longest duration peaks, and the 4 average years with the shortest duration peaks, in parentheses.

Table 3. Duration of spring peak flows and observed sand depletion (2014–2018)

[based on data reported by Dean and others (2020)]

Year	Condition	Annual peak discharge (ft^3/s)[1]	Days above 8,300 ft^3/s	Days above 16,000 ft^3/s	Days above 22,000 ft^3/s	Days above 24,000 ft^3/s	Degree of sand depletion during runoff
2014	Average	20,800	49	21	0	0	Moderate
2015	Moderately dry	16,200	45	0	0	0	Moderate
2016	Average	24,400	62	28	9	1	Substantial
2017	Wet	22,100	115	33	0	0	Substantial
2018	Average	13,000	29	0	0	0	Low

[1]Annual instantaneous peak discharge at Green River, Utah.

duration peak flows are more likely to cause greater depletion of the upstream sediment supply, causing greater reductions in suspended sediment concentration, greater increases in the bed and suspended-sand grain size, and decreasing the likelihood of deposition along channel margins and floodplains (Dean and others, 2020). In essence, longer-duration peak flows that do not go overbank will cause sediment depletion/erosion in the channel by exporting sediment downstream and not by depositing this sediment on the margins and floodplains. Longer duration peak flows may increase the likelihood of erosion in some locations, such as side channels around islands, that would not have eroded over the duration of a shorter flood (Grams and others, 2020). The peak-flow duration required to create conditions of sediment depletion is imprecisely understood and likely varies depending on relative level of sand enrichment before the annual flood (Dean and others, 2020). Based on limited observations, peak-flow durations of 4 or more weeks above 16,000 ft^3/s are likely required to create these conditions of relative sand depletion. For typical hydrographs, this requirement likely equates to 60 days or longer above 8,300 ft^3/s.

The combined maximum capacity of the powerplant and bypass at Flaming Gorge Dam is 8,600 ft^3/s. [1] Releasing higher discharge requires use of the spillway, which is limited to situations where this is necessary to maintain dam safety. Furthermore, current Reclamation procedures are designed to avoid spillway usage even during extremely high runoff (LaGory and others, 2019). LaGory and others (2019) have concluded that the 8,600 ft^3/s (± 600 ft^3/s) release limit would have prevented attainment of recommended peaks or durations in 8 out of the 24 years classified as average wet, moderately wet, or wet from 1963 to 2017. Modifying the Reclamation policy of severely limiting spillway use would greatly increase the ability to prescribe channel widening flows in any hydrologic condition. The costs of such a policy modification, especially the cost of safely reengineering the spillway for more frequent use, are not currently known.

[1]This capacity is based on the maximum powerplant capacity of 4,600 ft^3/s and bypass capacity of 4,000 ft^3/s reported by Reclamation. However, mean daily streamflow at the Green River near Greendale, Utah, gaging station 09234500, immediately downstream from the dam, during peak streamflow when only the powerplant and bypass facilities are in operation has been as high as 9,220 ft^3/s (in 2020).

Peak-flow timing

Description of Recovery Program recommendation for peak flow-timing

For the segment of the Green River that includes Canyonlands National Park (reach 3), peak-flow timing depends on upstream runoff patterns and the recommendations for reaches 1 and 2. The recommendation for those upstream reaches is that peak flows should be timed in most years to coincide with the appearance of larval razorback suckers, which often means delaying peak releases from Flaming Gorge Reservoir until after the peak on the Yampa River. In years that the release from Flaming Gorge Reservoir is delayed relative to the Yampa River peak, this recommendation can have the effect of increasing the duration (and not the magnitude) of peak flows in the Green River downstream from the Yampa River confluence. However, during years that larval razorback suckers appear early, this recommendation can have the effect of increasing the magnitude (and not the duration) of peak flows in the Green River downstream from the Yampa River.

Physical and biological processes related to peak-flow timing

For a given peak-flow magnitude and duration, the timing is unlikely to have a direct impact on geomorphic processes. Because invasive tamarisk has a longer and later season of seed release than its native competitors, including Fremont cottonwood (*Populus fremontii*) and sandbar willow (*Salix exigua*), delaying flood peaks could have the potential to favor tamarisk (Friedman, 2018). However, along the Green River, razorback sucker larvae appear in late May to early June (LaGory and others, 2019), whereas tamarisk seed release does not begin until July (Cooper and others, 1999). Therefore, delaying peaks until razorback sucker larvae appear is not likely to promote tamarisk in the Green River case.

Implications of Recovery Program recommendation for peak-flow timing

The recommendations for peak-flow timing for reaches 1 and 2 may affect the magnitude and duration of the peak flows for reach 3. Based on the above description of the processes related to peak-flow magnitude and duration, Flaming Gorge Dam operations that increase peak-flow duration in years of average or wetter hydrologic conditions are most likely to create conditions that favor sand-supply depletion and maintain channel form. In moderately dry and dry years, operations that increase peak-flow magnitude are most likely to avoid conditions that favor vegetation establishment and prevent future channel narrowing, whereas operations that increase peak-flow duration while substantially reducing peak-flow magnitude may promote vegetation establishment and channel narrowing.

Rate of decline from peak flow to base flow

The natural shape of the snowmelt flood hydrograph in the Green River in Canyonlands National Park is assymetric, with a gradual rising limb and more rapid recession (Dean and others, 2020). LaGory and others (2019) make no recommendation for rate of decline from peak flows to base flows for reach 3. The only recommendation for rate of decline from peak flow is for reach 1, which specifies that the decline from peak flow should be as fast as possible, but less than 2,000 $ft^3/s/day$, to begin base flows as early as possible. This is a change from the earlier recommendation of Muth and others (2000) for a gradual decline. The rate of decline from peak flows in Canyonlands National Park will also depend largely on the hydrograph from the unregulated Yampa River. A faster rate of decline from peak flow not only mimics the shape of the natural snowmelt hydrograph, but also frees up water that could be used to increase the magnitude or duration of peak flows that may inhibit channel narrowing. Rapid declines can also work against channel narrowing by drying sediment around roots of plant seedlings, which reduces establishment of riparian vegetation (Friedman, 2018). Conversely, this freed up water could be used to increase the magnitude or duration of base flows, thereby promoting narrowing.

Base-flow magnitude

Description of Recovery Program recommendation for base flows

Although not strictly defined, base flows are generally considered to be the quasi-steady flows that begin following the decline of the snowmelt flood and extend through the winter until the onset of the next spring runoff. In the pre-dam period, the onset of base flows varied from as early as July in dry years to as late as late-August in wet years (fig. 4). Operation of Flaming Gorge Dam has generally ended peak flows earlier than in the period before dam completion, resulting in flows that are lower than the pre-dam average was in July and August but higher than the pre-dam average was in September through February (fig. 4). Since 2006, base-flow recommendations have followed Muth and others (2000) on the basis of hydrologic condition. LaGory and others (2019) recommend experimental base flows for the summer months through September on a trial basis. Operations would revert to the recommendations of Muth and others (2000) after September, or earlier if low reservoir levels or other conditions do not allow application of the experimental base flows. Below, we address the non-experimental (Muth and others, 2000) and experimental base flows (LaGory and others, 2019) separately. Importantly, the base-flow recommendations of LaGory and others (2019) and Muth and others (2020) include flows that far exceed the lower base flows that nautrally occurred in the Green River.

Physical and biological processes related to base-flow magnitude

Low flows generally have a negligible direct effect on geomorphic processes along the Green River. At natural base flows, sediment-transport rates are low, and sediment contributed by tributaries likely accumulates on the riverbed until the following spring runoff season. However, regulated base flows are higher than natural base flows and can therefore have both direct and indirect effects on geomorphic processes. Because riparian vegetation is integral to floodplain formation by stabilizing banks and promoting fine-sediment deposition, any phenomenon that promotes vegetation growth and recruitment success can contribute to floodplain expansion. Elevated baseflows raise the water table, reducing summer drought stress and promoting establishment and density of riparian vegetation (Friedman, 2018). Denser vegetation increases drag on the flow, thereby promoting sediment deposition and leading to channel narrowing and simplification (Griffin and others, 2005). Additionally, sediment can be suspended and transported at the recommended base flows, which include flows as high as 4,700 ft^3/s. Sediment-transport data collected by the USGS since 2012 at four gaging stations along the Green River between Flaming Gorge Dam and Canyonlands National Park show that substantial sand, silt, and clay transport can occur at flows approaching 4,700 ft^3/s (https://www.gcmrc.gov/discharge_qw_sediment/). Thus, elevated base flows can result in deposition among the plants along the channel margins thereby contributing to channel narrowing.

Description of Recovery Program recommendation for non-experimental base flows

Regulation by Flaming Gorge Dam has resulted in higher base flows for all downstream reaches. Between 1931 and 1962, the average August–February flow at Green River was 2,030 ft^3/s. Between 1963 and 1999, the average August–February flow was 3,510 ft^3/s and from 1999 to 2018, the average was 2,480 ft^3/s. The non-experimental base flow recommendations range from 1,300 ft^3/s to 4,700 ft^3/s summer through winter, depending on hydrologic conditions (Muth and others, 2000; table 4, this report). The minimum range of the recommendations, which have been in operation since 2006, are similar to pre-dam August–February base flows whereas the maximum recommendations are substantially above pre-dam August–February base flows. The maximum recommended mean base flows are 165–200 percent higher than pre-dam mean base flows (table 4). Based on the Mineral Bottom stage-discharge relation, this represents elevated water tables of 0.25 to 0.52 meters.

Implications of Recovery Program recommendation for non-experimental base flows

Elevated base flows potentially increase the likelihood of channel narrowing by creating conditions that are likely to favor recruitment and establishment of riparian vegetation. The chance of this occurring is likely greatest during dry and moderately dry years, when elevated base flows follow low snowmelt floods and is exacerbated when multiple such years occur in succession.

There is also a potential indirect effect of increased base flows resulting from the redistribution of water volume that is required to elevate base flows. Achievement of elevated base flows requires water that could otherwise be used during the snowmelt flood. Thus, artificially increasing the base flows indirectly causes the peak flow to be of either lower magnitude or shorter duration. This condition likely has greatest effect in dry and moderately dry years, when peak-flow magnitude and duration are most constrained. Thus, elevated base flows during these years would increase the likelihood of reduced average peak flow over ~5-year periods, thus promoting channel narrowing. Furthermore, elevated base flows would reduce flood duration, thereby curtailing the sediment depletion in longer floods that could counteract channel narrowing.

Description of Recovery Program recommendation for experimental summer base flows

The recommended experimental base flows reduce base-flow variability within and between years. These recommendations increase base flows in dry years, decrease base flows in wet years, and decrease flow variability within and between years of a given hydrologic condition (table 5).

Implications of Recovery Program recommendation for experimental summer base flows

Experimental summer base flows for the lower Green River will incrementally intensify the increase and stabilization of base flows embodied in the non-experimental base flows. Increases in summer base flows in dry years will decrease drought stress, promoting the establishment of riparian vegetation, including invasive tamarisk, at elevations just above the base flow level on surfaces inundated by a discharge of roughly 2,000–3,800 ft^3/s along the lower Green River (table 5). Similarity in base flows between years helps vegetation established in one year to survive in the following year, increasing the likelihood of long-term plant survival. This vegetation increases fluid drag, reducing flow velocity, leading to sediment deposition (Griffin and others, 2005). Elevated and stabilized base flows will likely remove vegetation below the new base-flow level, resulting in a more pronounced lower vegetation boundary with a corresponding break in elevation. Decreases in peak-flow duration or magnitude would decrease the river's ability to erode riparian vegetation seedlings, leading to further vegetation encroachment and sediment deposition. This could lead to a reduced channel migration rate, steepening of channel banks, and a reduction in channel area at flows just above the base-flow level. Denser vegetation could resist flood erosion and rejuvenation of backwaters used by the Colorado pikeminnow. Consequently, the proposed

Table 4. Description of observed base flows and non-experimental (Muth and others, 2000) base flow recommendations.

[ft^3/s, cubic feet per second; m, meters]

Hydrologic condition	1930–1962 Aug.–Feb. mean flow (ft^3/s)[1]	1963–1999 Aug.–Feb. mean flow (ft^3/s)[1]	Minimum recommended base flow (ft^3/s)[2]	Maximum recommended base flow (ft^3/s)[2]	Increase from pre-dam to maximum recommended	Maximum stage difference at Mineral Bottom (m)[3]
Wet	2,790	4,670	3,200	4,700	169%	0.47
Moderately wet	2,780	4,260	2,700	4,700	169%	0.47
Average	2,130	3,490	1,800	4,200	197%	0.52
Moderately dry	1,780	2,220	1,500	3,400	191%	0.40
Dry	1,580	2,330	1,300	2,600	165%	0.25

[1]Based on analysis of mean daily flows and hydrologic condition at Green River, Utah (Appendix A).

[2]From table 5 and 6 in LaGory and others (2019).

[3]The amount by which maximum recommended base flows increase water surface elevation at Mineral Bottom compared to average pre-dam base flows for each hydrologic condition.

Table 5. Description of experimental summer base flows.

[ft^3/s, cubic feet per second; m, meters]

Hydrologic condition	Minimum recommended base flow (ft^3/s)	Stage difference at Mineral Bottom (m)	Maximum recommended base flow (ft^3/s)	Stage difference at Mineral Bottom (m)
Wet	2,800	0.0	3,800	0.3
Moderately wet	2,600	0.0	3,200	0.1
Average	2,300	0.0	2,800	0.2
Moderately dry	2,000	0.1	2,300	0.1
Dry	1,700	0.0	2,000	0.1

[1]From tables 5 and 6 in LaGory and others (2019).

[2]The amount by which recommended base flows increase water surface elevation at Mineral Bottom compared to average pre-dam base flows (table 4) for each hydrologic condition.

flow modifications could benefit the endangered Colorado pikeminnow in the short-term while degrading habitat for the same species in the long-term as channel narrowing is associated with sediment infilling of backwater habitats. Although the increases in recommended base flows in dry, moderately dry and average years are small relative to the non-experimental flows in the lower Green River, these increases would be larger for the middle Green River, between the Yampa River confluence and Green River, Utah (LaGory and others, 2019), requiring substantially increased flow releases from Flaming Gorge Dam. This action could decrease water available for the peak flow duration or magnitude of the annual high flow.

Base-flow period

LaGory and others (2019) make no recommendation for base-flow period for reach 3. They recommend that the base-flow period in reach 2 begin early in the summer, which will effectively reduce peak-flow durations. The experimental base-flow period extends through September and the non-experimental base-flow period extends through the following February. The base-flow period recommendation has a similar effect as the base-flow magnitude recommendations. Water from Flaming Gorge Reservoir that is used for extending the base flow period likely results in less water available for either increasing the magnitude or extending the duration of the snowmelt flood. The resultant effect on sediment dynamics and geomorphology is therefore likely to be greatest in dry and moderately dry years.

Base-flow variation

LaGory and others (2019) make no specific recommendations for base-flow variation for reach 3. The recommendations for reach 2 are that release fluctuations from Flaming Gorge Dam should not result in greater than 0.10 m daily stage change at the USGS Green River 09261000 gaging station near Jensen, Utah. The report also recommends mean daily flows are within ±40 percent of the annual mean base flow in summer and fall (August through November) and within ±25 percent of the annual mean base flow in winter (December through February). This recommendation is unlikely to have any direct effect on sediment dynamics and geomorphology; however, recommended reductions in base-flow variability will promote vegetation encroachment, as described in the "Physical and biological processes related to base flow magnitude " section.

Experimental spike flows

LaGory and others (2019) recommend spike flow releases of 4,500 ft^3/s of cool water for 3 days from Flaming Gorge Dam at the beginning of the base-flow period in mid-June, especially in dry years, to reduce the spawning success of invasive smallmouth bass in reach 2. The spike flows are different from the annual peak flows because they occur after peak-flow recession and are of lower magnitude than the peak flow. These spike flows are experimental and the recommendation is to test and evaluate in average or drier years. The spike flows are unlikely to directly affect sediment dynamics or geomorphology. However, those releases would also require water that could otherwise be used to increase peak-flow magnitude or duration to maintain channel width and backwater habitats.

Spike flows could either result in the removal of plant seedlings established earlier in the year at elevations between the stages corresponding to base flow and the spike peak or promote survival of plant seedlings growing near the elevation of the spike peak by irrigating those seedlings. Survival of these seedlings could be reduced by rapidly decreasing discharge back to base flow after the spike (Friedman, 2018). Completing spikes before the beginning of tamarisk seed dispersal, roughly July 1st (Friedman, 2018), would reduce the likelihood of promoting invasive species growth and channel narrowing (Manners and others, 2014). Climate warming could cause earlier seed release; therefore, monitoring of the timing of tamarisk seed release in future years could help to ensure that seeds are not present during spike flows.

Summary

For the purposes of this discussion, we define “geomorphic objectives” as flows that promote conditions of sediment transport and geomorphic change that are likely to result in maintenance of channel complexity and width. Channel complexity requires a dynamic channel with large amounts of erosion and deposition. This dynamism is dependant on flow variability, including peak-flow magnitudes high enough to mobilize sediment and uproot encroaching vegetation, peak-flow durations long enough to deplete the sediment supply within the river channel and to drown encroaching vegetation that cannot be uprooted, and base flows low enough to kill encroaching vegetation through desiccation. Sediment depletion during the spring snowmelt flood due to net erosion is necessary for maintenance of a dynamic channel and may contribute to channel widening. However, even floods that cause net erosion may also cause local deposition in regions of spatially decelerating flow. Thus, shorter, larger peak flows that favor deposition on floodplains and minimize erosion may promote channel narrowing, hence the need for longer duration floods to maintain channel width.

The recommendations by LaGory and others (2019) for peak-flow magnitude and duration in wet years are consistent with geomorphic objectives and historic post-dam flows. In moderately wet years, the recommended peaks may be sufficient to prevent narrowing over the short term, though they are lower than historical post-dam peaks and could allow for reduction in the occasional large peaks necessary to maintain channel complexity and mobility. For average and drier years, the recommendations allow, but do not require, peak-flow magnitude and durations that are likely to achieve geomorphic objectives in Canyonlands National Park. In average years, when peak flows are likely to be 22,000 cubic feet per second (ft^3/s) or greater, water from Flaming Gorge Reservior could be used to extend the duration of the snowmelt flood and increase the likelihood of meeting geomorphic objectives in Canyonlands National Park. In moderately dry and dry years, when peak-flow magnitude is likely to be low, geomorphic objectives might be best achieved by using water from Flaming Gorge to increase the magnitude of the snowmelt flood. Although the LaGory and others (2019) recommendations would allow releases to meet these objectives in average and drier years, the recommendations do not ensure these objectives are met and could result in releases that do not increase peak-flow duration in average years and do not increase peak-flow magnitude in dry and moderately dry years. Furthermore, the peak-flow magnitude and duration recommendations in dry and moderately dry years are substantially less than typically observed for those hydrologic conditions. During these hydrologic conditions, the revised recommendations could contribute to channel narrowing in that they might allow for the encroachment of riparian vegetation within the active channel, especially during multi-year droughts.

The LaGory and others (2019) recommendations for non-experimental base flows are generally inconsistent with geomorphic objectives. Increasing base flows above historic levels promotes establishment and growth of riparian vegetation, which can facilitate channel narrowing. The proposed experimental base flow recommendations would incrementally extend the process of stabilizing base flows and increasing them in dry years. The recommendation to start the base-flow period as early as possible would decrease peak durations. Increases in base flows require water volume that could otherwise be used to increase peak-flow magnitude in dry and moderately dry years or peak-flow duration in average years. The recommendations for base flows are likely less important in moderately wet and wet years, when peak-flow magnitude and duration are likely to meet or exceed the minimums required for geomorphic objectives.

Proposed early summer spike flows to disadvantage smallmouth bass could slow plant encroachment by removing seedlings established prior to and below the peak elevation of the spike but could irrigate surviving vegetation around the elevation of the spike peak and promote establishment of vegetation after the peak. Negative effects of spike flows could be minimized by completing them before release of invasive tamarisk seeds and by rapidly reducing flows following the spike to desiccate new seedlings.

The current Bureau of Reclamation policy of avoiding spillway use at Flaming Gorge Dam prevents releases larger than 8,600 ft^3/s (± 600 ft^3/s), which will prevent necessary peak-flow magnitude and duration in some years (LaGory and others, 2019), leading to potential consequences for channel maintenance and endangered species habitat. The cost of retrofitting the dam to allow safe use of the spillway for these resources and to increase safety for passing floods in extremely wet years is unknown.

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Appendix 1—Estimating Hydrologic Condition 1931–1992

The flow recommendations of LaGory and others (2019) depend on annual runoff volume, which is categorized by hydrologic condition. Hydrologic condition is classified each year by the Bureau of Reclamation as dry, moderately dry, average, moderately wet, or wet. This classification is determined on May 1 each year based comparing projected flows for the upcoming spring runoff with exceedance of historic unregulated April–July inflow to Flaming Gorge Reservoir from 1963 to the year before the current year. Because the time period of the record used to determine hydrologic condition is constantly changing (increasing), consistency in the classification of hydrologic condition is unclear in the context of the long-term historical streamflow record. The criteria used to estimate hydrologic condition based on forecasted flow cannot be applied to the pre-dam record; therefore we used the record of estimated natural flow from the Green River near Greendale, Utah, gaging station 09234500 (https://www.usbr.gov/lc/region/g4000/NaturalFlow/documentation.html) to classify hydrologic condition consistently for the period of record. Although there was a dramatic decrease in runoff in the early 20th century, there has not been a significant long-term trend in annual or April to July flow volume since 1931 at this gaging station (fig. 1.1). This is consistent with the hydrological analysis of Walker and others (2020) for the Green River, Utah, gaging station. We then used the 1931–2018 record of April–July flows to estimate exceedance thresholds for wet, moderately wet, average, moderately dry, and dry years (fig. 1.2). The frequencies of occurrence for each hydrologic condition are 10 percent wet, 20 percent moderately wet, 40 percent average, 20 percent moderately dry, and 10 percent dry. Although the April to July volumes for the natural flow record for the Greendale gaging station are larger than the reported inflow volumes (https://www.cbrfc.noaa.gov/wsup/graph/front/espplot_dg.html?year=2021&id=GRNU1), the correlation between the two records is very strong (fig. 1.3), indicating that categorization of hydrologic condition based on natural flows at the Greendale gaging station should be consistent with the categorization based on unregulated inflow. We applied those thresholds to the record to classify each year between 1931 and 2018 (table 1.1). In 14 out of the 23 years between 1993 and 2015, the hydrologic condition we estimated was the same as that determined by the forecasted inflows to Flaming Gorge Dam reported by LaGory and others (2019). During 8 of the 23 years, the hydrologic condition we estimated was one category wetter than was forecasted and in 1 of those 23 years, the hydrologic condition we estimated was one category drier than was forecasted. These discrepancies arise from two factors. First, the Bureau of Reclamation (hereafter Reclamation) uses the entire period from 1963 to the most recent year to

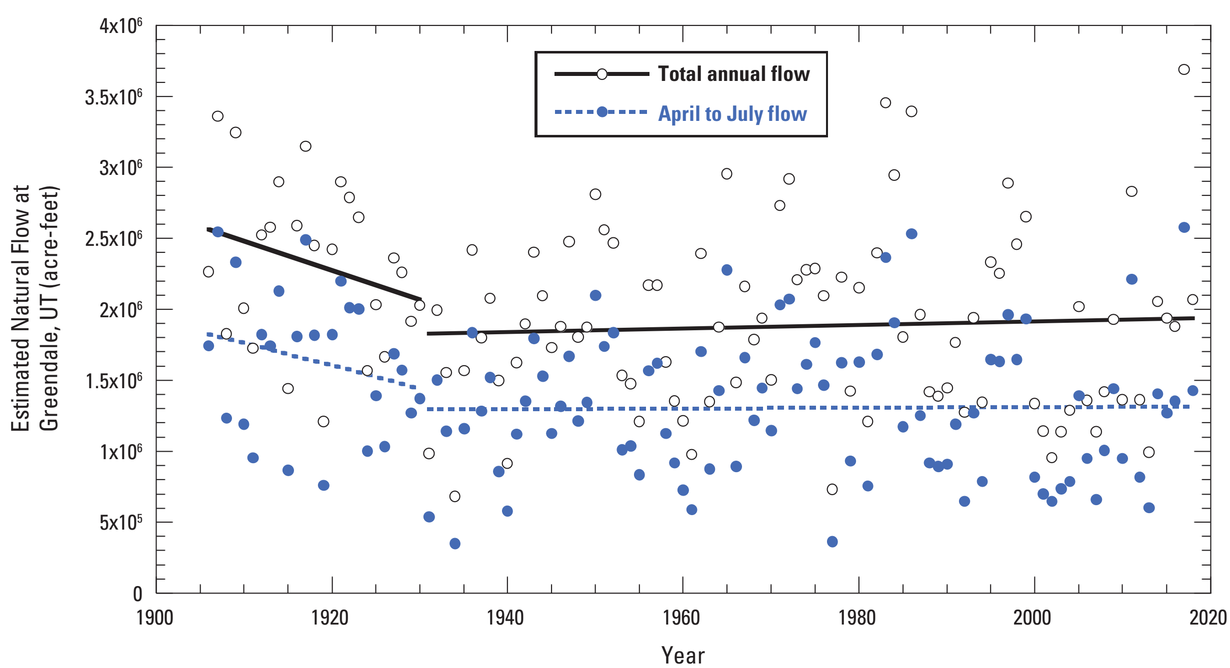

Figure 1.1. Plot of annual and April through July natural flow volumes in acre-feet estimated for the Greendale, Utah, gaging station from 1906 to 2018.

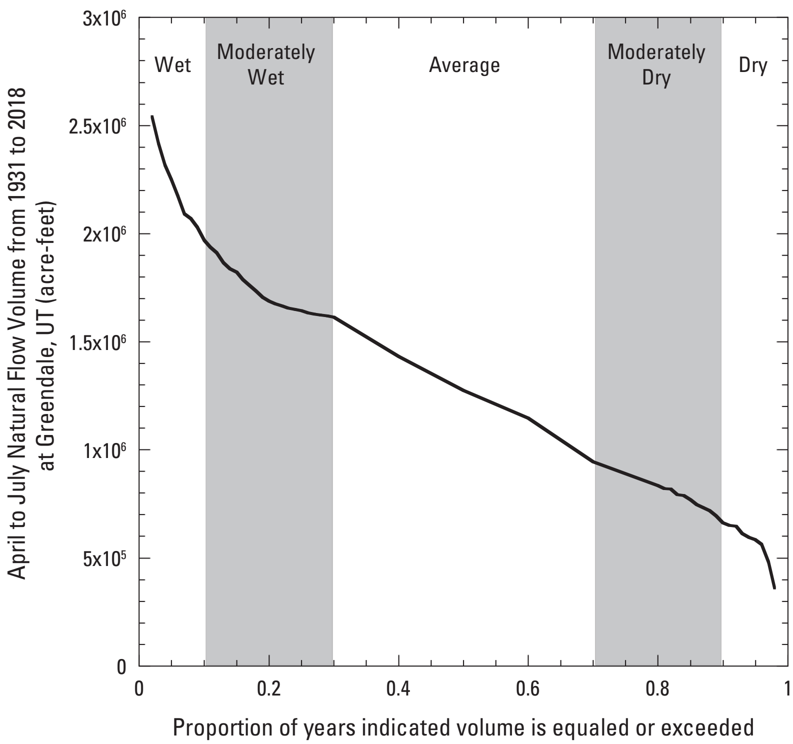

Figure 1.2. Plot of exceedance values in acre-feet for April through July flow volumes for the 1931–2018 record of natural flows at the Greendale, Utah, gaging station. Dry years are those with April–July volume of 662,000 acre-feet or less. Moderately dry years have April–July volume of 662,000–945,000 acre-feet. Average years have April–July volume of 945,000–1,615,000 acre-feet. moderately wet years have April–July volume of 1,615,000–1,970,000 acre-feet. Wet years have April–July volume greater than 1,970,000 acre-feet.

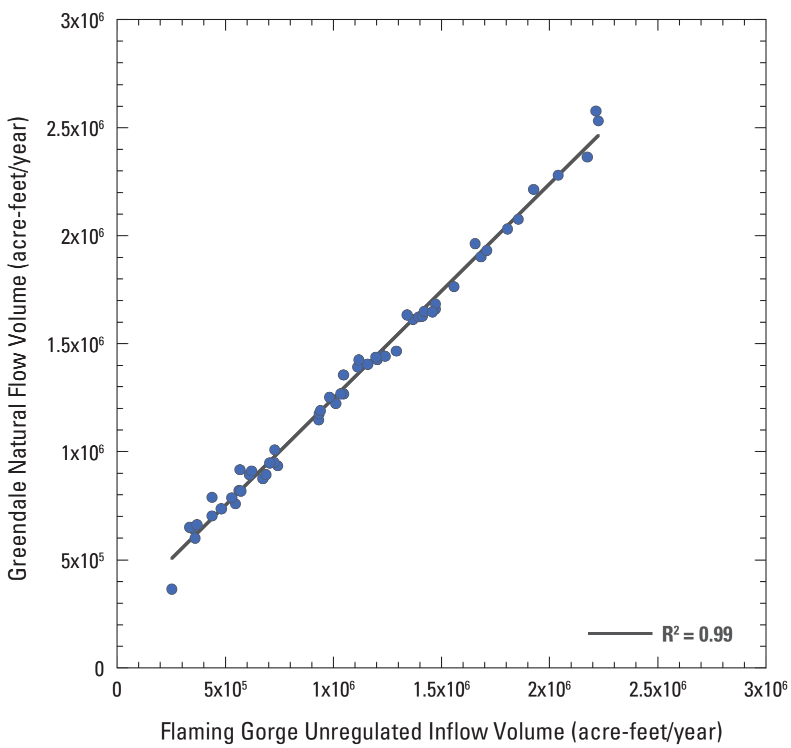

Figure 1.3. Plot of correlation between unregulated inflow volume in acre-feet per year for Flaming Gorge Dam and estimated natural flows for the Green River at Greendale, Utah (Bureau of Reclamation, 2020) in acre-feet per year.

develop the distribution used to estimate hydrologic condition, whereas we used a constant distribution (fig. 1.2) for the entire period. Secondly, the condition determined by Reclamation based on the May 1 runoff forecast may be different than the condition we determined based on observed runoff. We used the hydrologic condition that we estimated using the natural flow record for the Greendale gaging station only to compare hydrographs of mean daily flow before and after Flaming Gorge Dam was installed and where hydrologic condition is estimated for 1992 and earlier. Elsewhere in the report, we used the hydrologic condition determined by Reclamation and reported by LaGory and others (2019).

Table 1.1. Volume of April–July natural flows at Greendale, Utah from 1931 to 2018 and hydrologic condition based on those flows.

[ac-ft/year, acre feet per year; NA, hydrologic condition no specified.]

Year	April-July Natural Flow (ac-ft/yr)	Hydrologic Condition (Natural Flow Record)	Year	April-July Natural Flow (ac-ft/yr)	Hydrologic Condition (Natural Flow Record)	Hydrologic Condition (LaGory, 2019)
1931	540,568	Dry	1975	1,764,249	Moderately Wet	NA
1932	1,504,501	Average	1976	1,466,746	Average	NA
1933	1,144,524	Average	1977	364,538	Dry	NA
1934	351,423	Dry	1978	1,625,223	Moderately Wet	NA
1935	1,161,020	Average	1979	934,790	Moderately Dry	NA
1936	1,836,555	Moderately Wet	1980	1,629,016	Moderately Wet	NA
1937	1,281,412	Average	1981	758,642	Moderately Dry	NA
1938	1,520,816	Average	1982	1,684,354	Moderately Wet	NA
1939	858,525	Moderately Dry	1983	2,363,345	Wet	NA
1940	579,715	Dry	1984	1,902,843	Moderately Wet	NA
1941	1,122,117	Average	1985	1,176,739	Average	NA
1942	1,354,887	Average	1986	2,530,811	Wet	NA
1943	1,796,267	Moderately Wet	1987	1,253,320	Average	NA
1944	1,534,173	Average	1988	918,137	Moderately Dry	NA
1945	1,123,182	Average	1989	895,632	Moderately Dry	NA
1946	1,320,332	Average	1990	912,093	Moderately Dry	NA
1947	1,673,004	Moderately Wet	1991	1,190,982	Average	NA
1948	1,215,790	Average	1992	648,051	Dry	NA
1949	1,347,148	Average	1993	1,269,528	Average	Average
1950	2,098,349	Wet	1994	789,131	Moderately Dry	Dry
1951	1,737,780	Moderately Wet	1995	1,649,650	Moderately Wet	Average
1952	1,838,578	Moderately Wet	1996	1,634,687	Moderately Wet	Average
1953	1,013,780	Average	1997	1,963,164	Moderately Wet	Moderately Wet
1954	1,041,069	Average	1998	1,648,663	Moderately Wet	Moderately Wet
1955	837,637	Moderately Dry	1999	1,932,393	Moderately Wet	Moderately Wet
1956	1,569,758	Average	2000	821,194	Moderately Dry	Moderately Dry
1957	1,618,849	Moderately Wet	2001	702,990	Moderately Dry	Dry
1958	1,127,762	Average	2002	650,767	Dry	Dry
1959	917,852	Moderately Dry	2003	737,132	Moderately Dry	Dry
1960	727,593	Moderately Dry	2004	787,862	Moderately Dry	Moderately Dry
1961	590,385	Dry	2005	1,393,388	Average	Average
1962	1,704,075	Moderately Wet	2006	951,090	Average	Average
1963	877,117	Moderately Dry	2007	663,780	Moderately Dry	Moderately Dry
1964	1,427,710	Average	2008	1,008,635	Average	Average
1965	2,280,334	Wet	2009	1,439,362	Average	Average

Table 1.1. Volume of April–July natural flows at Greendale, Utah from 1931 to 2018 and hydrologic condition based on those flows.—Continued

[ac-ft/year, acre feet per year; NA, hydrologic condition no specified.]

Year	April-July Natural Flow (ac-ft/yr)	Hydrologic Condition (Natural Flow Record)	Year	April-July Natural Flow (ac-ft/yr)	Hydrologic Condition (Natural Flow Record)	Hydrologic Condition (LaGory, 2019)
1966	895,656	Moderately Dry	2010	949,942	Average	Moderately Dry
1967	1,662,478	Moderately Wet	2011	2,213,903	Wet	Moderately Wet
1968	1,222,063	Average	2012	819,368	Moderately Dry	Moderately Dry
1969	1,446,992	Average	2013	601,861	Dry	Moderately Dry
1970	1,146,513	Average	2014	1,406,398	Average	Average
1971	2,031,118	Wet	2015	1,267,712	Average	Moderately Dry
1972	2,075,030	Wet	2016	1,357,519	Average	NA
1973	1,442,124	Average	2017	2,577,678	Wet	NA
1974	1,612,934	Average	2018	1,426,297	Average	NA

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