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Potential Effects of Elevated Base Flow and Midsummer Spike Flow Experiments on Riparian Vegetation along the Green River

Natural Resource Report NPS/NRSS/WRD/NRR—2018/1603

ON THE COVER
Island Park, Green River, Dinosaur National Monument
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Potential Effects of Elevated Base Flow and Midsummer Spike Flow Experiments on Riparian Vegetation along the Green River

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Jonathan M. Friedman

U.S. Geological Survey
2150 Centre Avenue, Building C
Fort Collins, CO 80526

March 2018

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

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Please cite this publication as:

Friedman, J. M. 2018. Potential effects of elevated base flow and midsummer spike flow experiments on riparian vegetation along the Green River. Natural Resource Report NPS/NRSS/WRD/NRR—2018/1603. National Park Service, Fort Collins, Colorado.

NPS 909/143192, March 2018

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Executive Summary

The Upper Colorado River Endangered Fish Recovery Program has requested experimental flow releases from Flaming Gorge Dam for (1) elevated summer base flows to promote larval endangered Colorado pikeminnow, and (2) midsummer spike flows to disadvantage spawning invasive smallmouth bass. This white paper explores the effects of these proposed flow modifications on riparian vegetation and sediment deposition downstream along the Green River. Although modest in magnitude, the elevated base flows and possible associated reductions in magnitude or duration of peak flows would exacerbate a long-term trend of flow stabilization on the Green River that is already leading to proliferation of vegetation including invasive tamarisk along the channel and associated sediment deposition, channel narrowing and channel simplification. Midsummer spike flows could promote establishment of late-flowering plants like tamarisk. Because channel narrowing and simplification threaten persistence and quality of backwater and side channel features needed by endangered fish, the proposed flow modifications could lead to degradation of fish habitat. Channel narrowing and vegetation encroachment could be countered by increases in peak flows or reductions in base flows in some years and by prescription of rapid flow declines following midsummer spike flows. These strategies for reducing vegetation encroachment would need to be balanced with flow needs of other riverine resources. Use of high flows to remove unwanted vegetation is constrained by current operational guidance for Flaming Gorge Dam, which attempts to limit spills (i.e., flows greater than 8600 ft^3/s) that might contribute to cavitation and lead to dam safety concerns. Therefore, reversing vegetation encroachment is more likely to succeed if implemented while plants are still small. Annual monitoring of near-channel vegetation and topography would enable managers to prescribe a timely hydrologic response in case the proposed flow experiments lead to vegetation encroachment and habitat degradation.

Acknowledgments

This work was funded by the National Park Service's Colorado River Program. Reviews were provided by Jennifer Rebenack, Mark Wondzell, Melissa Trammell, Terry Fisk, Dusty Perkins, Rob Billerbeck, and Greg Auble. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Introduction

The Upper Colorado River Endangered Fish Recovery Program (Recovery Program) has requested that the Bureau of Reclamation conduct experimental elevated base flows from mid-July through September by releasing water from Flaming Gorge Dam to improve survival of larval endangered Colorado pikeminnow (*Ptychocheilus lucius*) in nursery backwater habitats (Bestgen and Hill 2016a). The Recovery Program is also requesting experimentation with a midsummer (ca July) spike flow lasting several days to disadvantage spawning success of invasive smallmouth bass (*Micropterus dolomieu*, Bestgen and Hill 2016b), a non-native invasive species known to prey upon pikeminnow and other native fishes. This white paper addresses the potential effects of these proposed flow modifications on riparian vegetation and sediment deposition along the Green River in Colorado and Utah, from Flaming Gorge Reservoir to the confluence with the Colorado River (Figure 1). Although all plant species are considered here, there is a focus on tamarisk (*Tamarix* sp.), an invasive species whose proliferation in response to past reductions in flow variability has been linked to channel narrowing along the Green River (Birken and Cooper 2006, Manners et al. 2014).

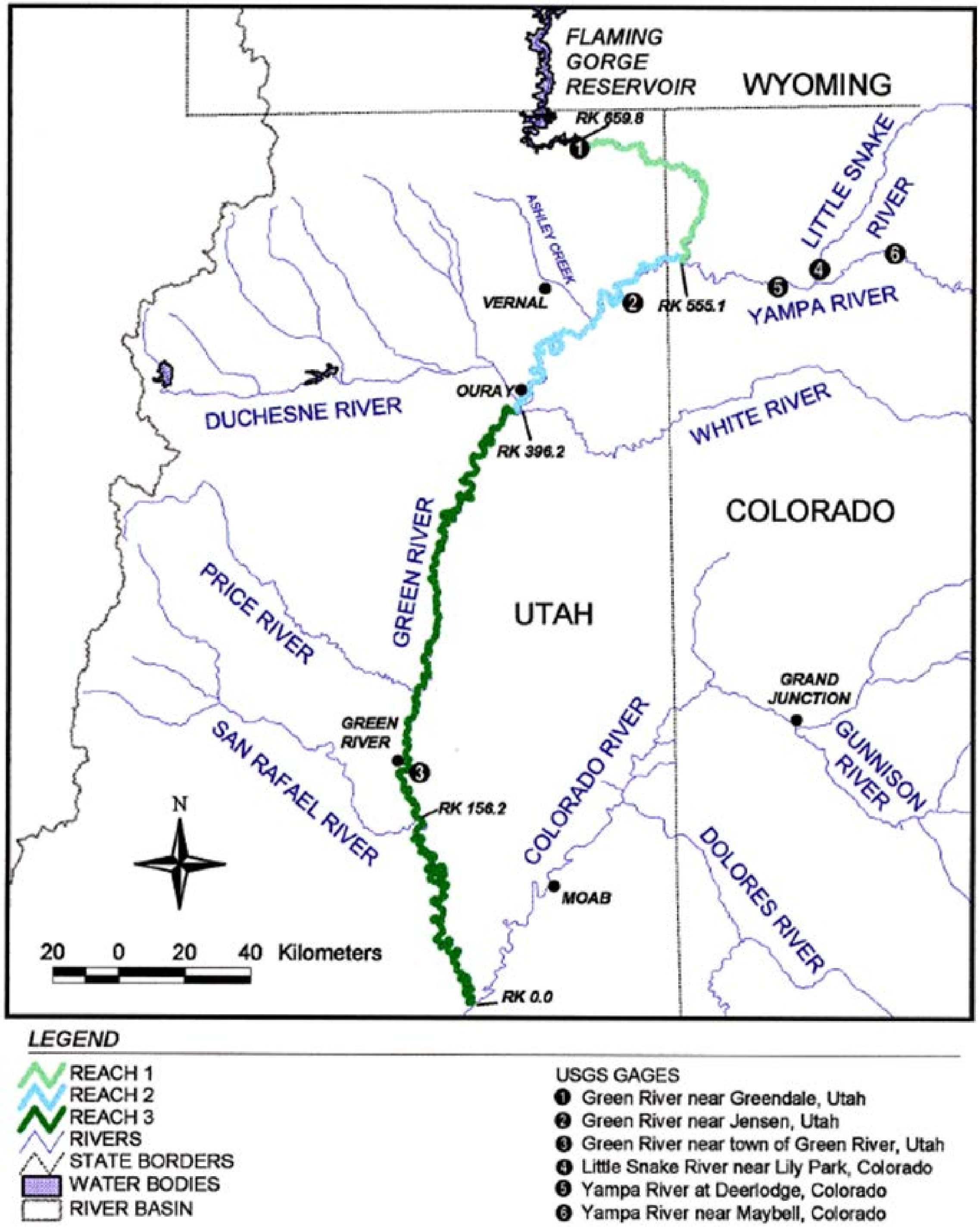

Figure 1. Map showing reach divisions and USGS stream gages (excerpted from Muth et al. 2000).

Flow Variability and Riparian Vegetation in General

Flow variability reduces vegetation cover, promotes disturbance-dependent plant species and maintains a wide channel

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). Removal of some plants provides opportunities for establishment of others. Seedlings of many riparian species require moist sunny surfaces created by fluvial disturbance (Friedman et al. 1996). Lightly regulated rivers of western North America typically have large inter- and intra-annual flow variability, resulting in rapid channel movement, sparse vegetation near the channel and abundant opportunities for establishment of native disturbance-dependent "pioneer" species (Brinson et al. 1981, Naiman et al. 2005, Sabo et al. 2005, Bagstad et al. 2006). Where geology, precipitation patterns or flow regulation reduce flow variability, the result is a narrow channel bordered by dense vegetation with little opportunity for establishment of disturbance-dependent species (O'Connor and Grant 2003).

Reductions in streamflow magnitude and variability result in a correspondingly narrower river channel, as perennial terrestrial vegetation becomes established and traps sediment on the channel bed and banks. Thus flow regulation has caused channel narrowing and encroachment of riparian woody and herbaceous vegetation in western North America in general (Nadler and Schumm 1981, Williams and Wolman 1984, Everitt 1993, Johnson 1994, Friedman et al. 1998, Mortenson and Weisberg 2010) and the Colorado River system in particular (Allred and Schmidt 1999, Merritt and Cooper 2000, Cooper et al. 2003, Webb et al. 2011, Manners et al. 2014, Sankey et al. 2015). Along the regulated Green River decreases in peak flows have allowed establishment of pioneer riparian species, primarily tamarisk, on exposed bars, resulting in channel narrowing and simplification and development of a broad tamarisk forest (Grippo et al. 2016, Grams and Schmidt 2002, 2005). Between Flaming Gorge Dam and the Yampa River confluence this process has decreased channel width by 10-30% (Grams and Schmidt 2005). Perkins et al. (2015) found that the Green River above the confluence with the Yampa had the highest density of invasive plant patches, followed by the Green River below the confluence and the relatively unregulated Yampa. The Green River above the confluence with the Yampa also had significantly higher percent cover of tamarisk than the Yampa River.

Artificially raising extreme low flows leads to proliferation of species tolerant of extended inundation at the water's edge (Stevens et al. 1995). Along the Green River in Browns Park, increased low flows have resulted in inundation duration of 148 days per year on low-lying depositional bars and islands, compared to 43 days for comparable surfaces on the relatively unregulated Yampa River at Deerlodge Park (Merritt and Cooper 2000). On these low-lying surfaces at Browns Park, reduction in peak flows and increase in low flows have promoted development of anoxic soils and proliferation of dense marsh vegetation consisting of species tolerant of anoxia, such as common spikerush (*Eleocharis palustris*), knotted rush (*Juncus nodosus*), common threesquare (*Schoenoplectus pungens*) and sandbar willow (*Salix exigua*; Merritt and Cooper 2000). Surfaces of comparable elevation along the less regulated Yampa River at Deerlodge Park have lower inundation duration, are subject to shear stresses of higher frequency and magnitude, and are more sparsely vegetated. Dominant plants include annual and short-lived perennial species able to colonize new sites rapidly after disturbance, such as small ribseed sandmat (*Chamaesyce glyptosperma*), marsh cudweed (*Gnaphalium uliginosum*), water mudwort (*Limosella aquatica*), curlytop knotweed (*Persicaria lapathifolia*), rough cocklebur (*Xanthium strumarium*), and foxtail barley (*Critesion jubatum*; Merritt and Cooper 2000).

Hydrologically Relevant Ecological Requirements of Tamarisk

This section explores the mechanistic relation between flow and the establishment, survival and removal of tamarisk. Although tamarisk is not the only important riparian species along the Green River, I focus on it here because of its central role in ongoing channel narrowing in this system (Merritt and Cooper 2000) and because of the large body of information that has been developed about this species by past research.

Removal of tamarisk by desiccation, inundation and flood disturbance

The tiny seeds of tamarisk (around 0.1 mg, Perry et al. 2013) produce small seedlings that require continuous contact with moisture for survival. Seedlings are killed by a day or two of desiccation (Horton et al. 1960). Once the roots contact the water table they can grow downward rapidly. Where the channel boundary is dominated by sand and coarser particles, the water table closely follows the water surface elevation of the river. Although seedlings have been reported to survive water-table declines as large as 4 cm/day (Horton and Clark 2001), survival and growth are highest where water-table decline is less than 1.2 cm/day (Shafroth et al. 1998, Horton and Clark 2001). Where water table is static, above and below-ground growth of tamarisk seedlings is higher at a groundwater depth of 60 cm than at a depth of 100 cm (Li et al. 2012). Susceptibility of tamarisk to drought decreases with age as plants develop a more extensive root system.

Tamarisk flood tolerance increases strongly with age. Young seedlings 5 and 10 days old can be removed instantly by flooding because the roots are not strong enough to prevent uprooting due to the buoyancy of the seedlings (Horton et al. 1960). For older plants, mortality from prolonged inundation is associated with oxygen depletion in the root zone or exhaustion of energy reserves (Friedman and Auble 1999). First-year seedlings with enough roots to avoid uprooting through buoyancy may be killed by flooding lasting tens of days. For example, in a Colorado study, fall flooding for 25 days resulted in 0.8% survival for tamarisk seedlings (Gladwin and Roelle 1998), and in a New Mexico study, seedling survival after 30 days of fall flooding was 43.5% for 6-8-week-old tamarisk seedlings and 2% for 4-week-old tamarisks (Sprenger et al. 2001). Mature tamarisk can survive complete submergence during the growing-season for up to 70 days and partial submergence for up to 98 days (Warren and Turner 1975). In a Kansas Lake less than 4% (40 out of thousands) of tamarisk survived inundation for one year (Tomanek and Ziegler 1962).

Woody plants are subject to removal by mobilization of underlying sediment (Friedman and Auble 1999) or by damage from rapidly flowing water, sediment and woody debris (Hupp and Osterkamp 1985). Whereas removal by extended inundation is a function of flow duration, removal by sediment mobilization or debris damage is a function of flow magnitude. The percentage of bottomland cleared by the two factors can be modeled on the basis of flow data and a stage-discharge relation (Friedman and Auble 1999).

Seedling establishment of tamarisk occurs on sites moistened and disturbed by the river in both high and low-flow years

Tamarisk and other riparian pioneer species produce abundant, mobile seeds that must germinate within weeks after dispersal. Seeds germinate to tiny seedlings that require abundant light and moisture. Therefore, in any year, seedling establishment is limited to the zone irrigated and disturbed by the river at the time of seed release (Scott et al. 1996, Glenn and Nagler 2005). On a floodplain cross section the high limit of this zone is the stage of the peak discharge, as long as the discharge did not occur more than a few weeks before the period of seed release (Auble and Scott 1998, Manners et al. 2014). Seedling establishment near the high limit is further constrained by desiccation caused by river stage declining more rapidly than root extension (Mahoney and Rood 1998, Shafroth et al. 1998, Horton and Clark 2001). The low limit of the establishment zone is roughly the stage at the end of the period of seed dispersal (Manners et al. 2014). Because small seedlings have very limited ability to survive desiccation or flooding, plants may be killed by flow fluctuations, especially early in life, reducing the size of the observed zone of establishment (Auble and Scott 1998), but susceptibility to such flow fluctuations decreases with age. Because a zone of successful seedling establishment may occur in a high-flow or low-flow year, establishment of tamarisk, cottonwood and willow can occur at a wide range of elevations (Cooper et al. 2003, Birken and Cooper 2006, Manners et al. 2014).

Tamarisk has a longer and later season of seed release than native competitors, allowing tamarisk to reproduce following late season peaks and to become established low on the channel bank

Seeds of invasive tamarisk and native competitors Fremont cottonwood (*Populus deltoides* ssp. *wislizenii*) and sandbar willow lack dormancy and have short longevity. Therefore, they must find a suitable environment for germination within weeks of dispersal. Fremont cottonwood and sandbar willow seeds are released for a short period in spring or early summer, often coinciding with the declining limb of flow peaks in unregulated rivers (Stella et al. 2006). In contrast the season of tamarisk seed release tends to start later than that of cottonwood and willow (Ralston et al. 2014) and extends through most of the growing season (Warren and Turner 1975, Stromberg 1997). For example, at Island Park in 1993 and at Browns Park in 1994 and 1995, tamarisk seed dispersal along the Green River began in early to mid-July, and continued until early September (Cooper et al. 1999).

Because of the extended season of tamarisk seed release, mid- to late-summer peaks promote establishment of tamarisk over native cottonwood and willow (Everitt 1995, Cooper et al. 2003, Stromberg et al. 2007, Merritt and Poff 2010, McShane et al. 2015). For example, operation of Flaming Gorge Reservoir on the Green River resulted in seasonal delay of peak flows downstream in 1975 and 1983 (July 7, 1975 and July 8, 1983 at Greendale Utah, Gage 9234500). In these two years tamarisk but not cottonwood became established at Browns Park. In contrast, peak flows in 1984 and 1986 were earlier (May 7, 1984 and May 20, 1986) and led to recruitment of cottonwood (Cooper et al. 2003). For this reason midsummer (July or later) flow spikes, such as those proposed by the Recovery Program, would favor tamarisk over native woody species.

Because tamarisk seed release continues much later in the season than that of cottonwood and willow, the tamarisk zone of establishment extends down closer to the river. This is because tamarisk seeds are available to germinate during low flows in midsummer on surfaces covered by water during the period of cottonwood and willow seed release (Manners et al. 2014). For example, in Yampa Canyon, cottonwood establishment occurred from 75 to 300 cm above the elevation of base flow, while tamarisk establishment extended down to around 25 cm above the elevation of base flow (Cooper et al. 2003).

Tamarisk strongly promotes sediment deposition and channel narrowing

Fluid drag on woody stems decreases local flow velocity, reducing erosion and promoting deposition of fine-grained sediment (Manners et al. 2013, 2014). Fluid drag is proportional to stem diameter not stem cross-sectional area. For example, two cylindrical stems each 3 cm in diameter have a similar effect on flow to that of one stem 6 cm in diameter, even though the latter stem contains twice as much wood. Although trees like box elder (*Acer negundo*) and cottonwood have thick stems, the fluid drag they exert is less than that of shrubs like sandbar willow and young tamarisk (Graf 1978) because shrubs have far more stems than trees (Griffin et al. 2014, Manners et al. 2015). Relative to those of sandbar willow, tamarisk stems are less flexible, tending to stay upright during floods. Therefore tamarisk has a stronger effect than sandbar willow on flow velocity and sediment deposition (Griffin and Smith 2004). In summary, of these 4 dominant woody species, tamarisk most strongly promotes floodplain construction by fine sediment deposition (Manners et al. 2014, 2015). In the widest reaches of Yampa Canyon, increase in tamarisk in the 1980s led to channel narrowing by sediment deposition in the 1990s (Manners et al. 2014). Removal of riparian vegetation dominated by tamarisk resulted in erosion and widening of the Rio Puerco, New Mexico (Vincent et al. 2009). Promotion of sediment deposition by tamarisk increases with age. In Yampa Canyon, modest sediment deposition has been observed around stems 1-2 years old, but the most rapid sediment deposition has occurred in stands roughly a decade old (Manners et al. 2014).

The ability of tamarisk to disperse seeds throughout the summer allows it to become established at low elevations adjacent to the channel. Tolerance of inundation and scouring, and the ability to enhance sediment deposition, enable the tamarisk to persist adjacent to the channel. The high density of relatively stiff stems creates a large fluid drag, promoting sediment deposition, reducing damage to the tamarisk by flood inundation and disturbance. Drought tolerance of adults allows the tamarisk to survive even after sediment deposition has raised the surface elevation. In trenches at Laddie Park in Yampa Canyon, 84% of excavated tamarisks germinated below the stage of the 2-year flood (Manners et al. 2014).

Two or more years in a row with similar flows promote establishment of woody vegetation, and subsequent sediment deposition around this vegetation can lead to channel narrowing

Seedlings of tamarisk and cottonwood are susceptible to removal in subsequent years by desiccation due to low flows or inundation and disturbance due to high flows. Establishment elevation in the first year determines the susceptibility to desiccation or inundation in the second year. Seedlings established high on the bank in a high-flow year will die from desiccation if flow is much lower in year two. Conversely, seedlings established low on the bank in a low-flow year will die from inundation or disturbance if the peak is larger in year two. Thus flow variability between years helps to maintain a wide channel and sparsely vegetated floodplain. In contrast, sequences of years with similar flows promote establishment of woody plants, mostly tamarisk in canyons (Manners et al. 2014) and both tamarisk and cottonwood in parks (Cooper et al. 2003). Once established the vegetation promotes sediment deposition and channel narrowing. Manners et al. (2014) found a strong increase since 1976 in the tendency for wet years to follow wet years and dry years to follow dry years along the Yampa River. They argue that this increase in interannual flow autocorrelation is responsible for the expansion of tamarisk in wide reaches of Yampa Canyon since the mid-1980s and subsequent channel narrowing. A similar sequence of events has occurred at Deerlodge Park, except that the new vegetation is dominated by both cottonwood and tamarisk (Merritt and Cooper 2000, Cooper et al. 2003). These changes in vegetation and channel width along the Yampa River have occurred in the absence of changes in mean annual flow peak or volume (Manners et al. 2014). Along the Green River, where the mean annual peak has been strongly decreased by flow regulation, tamarisk encroachment and channel narrowing have been far more extensive (Grams and Schmidt 2002, 2005, Manners et al., 2014).

Hydrological Tools for Preventing Establishment of Unwanted Riparian Vegetation

Within-year flow variability

Because seedlings are most vulnerable when young, plants can be efficiently removed by varying flow in the first few weeks after germination. Since germination tends to occur during periods of gradually declining flow, these periods can be a focus for efforts to remove seedlings using flow variation. Gradual flow declines promote seedling establishment if root growth is able to keep up with the declining water level. One way to prevent establishment of unwanted riparian vegetation during declining flows is to use dam releases to superimpose fluctuations on those flow declines. Temporary flow increases inundate and remove young seedlings by floating them out of the soil. Temporary rapid declines lasting at least a few days can kill young seedlings by desiccation. This technique has been used to control vegetation supporting malaria mosquitoes on reservoir margins in the southeastern United States (Hall et al. 1946). A second way to limit establishment of riparian vegetation following a flow peak is to remove periods of gradual decline from the hydrograph. For example, a gradual decline could be replaced by a period of slightly increasing flow followed by a rapid decline exceeding the rate of downward root growth. These approaches can be frustrated by weather. For example, rainfall could enable seedlings to survive a rapid decline in flow.

Between-year flow variability

At the multi-year scale, proliferation of riparian vegetation can be prevented by flow variation between years (Manners et al. 2014). For example, if high peak and base flows in one year promote establishment of tamarisk high above the channel, low flows in the following year can kill those plants by desiccation. Conversely, if low peak and base flows in one year promote establishment of tamarisk close to the channel, high flows in the following year can remove them by extended inundation or physical disturbance. Flow prescriptions for the same target peak or base flow in most years can promote the establishment of bathtub rings of dense vegetation (Rood et al. 2010).

Effects of Proposed Flow Alterations in the Green River and Options for Mitigation

Effects of elevated baseflows

The proposed elevated baseflows (Table 1) would reduce flow variability in the Green River in two ways. First, providing additional water for base flows could decrease the peak magnitude and/or duration in some years. Second, the lowest flows would be increased. Compared to the Flaming Gorge Flow Recommendations (Muth et al. 2000; Table 1) base flow stage would increase in dry years by an average of 21.61 cm and 11.73 cm in the Middle and Lower Green River (Table 2). In contrast, base flow stage would be essentially unchanged in wet years (Table 2). Thus the proposed changes would decrease within-year flow variability in drier years by raising base flows, and they would decrease between-year flow variability by reducing the difference in base flows between wet and dry years. These incremental changes add to decreases in flow variability already caused by (1) increases in base flows in the Flaming Gorge Flow Recommendations (Muth et al. 2000) relative to the 1992 Biological Opinion; and (2) flow-peak recommendations for razorback suckers in the Larval Trigger Study Plan (2012), which decrease peak flows in some years by constraining timing of high flow releases from Flaming Gorge Dam so that these high flows do not always coincide with peak flows in the less regulated Yampa River. All of these incremental changes compound the effects of the larger decrease in flow variation brought about by operation of Flaming Gorge Reservoir since 1964 (Merritt and Cooper 2000, U.S. Fish and Wildlife Service 2005; U.S. Department of the Interior 2006). The proposed increases in base flow could be justified by arguing that they are closer than current flows to the pre-regulation base flows (Bestgen and Hill 2016a). A problem with this argument is that peaks have been greatly reduced, and current operational guidance for Flaming Gorge Dam spillway limits peak releases to 244 m^3/s (8600 ft^3/s) because they might contribute to cavitation and lead to dam safety concerns. Reducing the difference between peak and base flows increases the density and area of riparian vegetation, promoting sediment deposition, channel narrowing and possibly channel simplification: a decrease in number or area of side channel and backwater habitats.

Table 1. Comparison of the elevated base flows proposed by the Recovery Program to the Flaming Gorge Flow Recommendations (Muth et al. 2000), excerpted from Bestgen and Hill (2016a). The higher upper ends of flow ranges in Muth et al. (2000) for the lower Green River reflect uncertainty about tributary inputs, while proposed targets represent preferred ranges (from Bestgen and Hill 2016a).

Hydrologic Classification	Reach 2, Middle Green River		Reach 3, Lower Green River	
	2000 (Muth)	**Proposed**	**2000 (Muth)**	**Proposed**
Dry (10% of years)	26–31 m^3/s *900–1,100 ft^3/s*	48–51 m^3/s *1,700–1,800 ft^3/s*	37–74 m^3/s *1,300–2,600 ft^3/s*	48–57 m^3/s *1,700–2,000 ft^3/s*
Moderately Dry (20% of years)	31–43 m^3/s *1,100–1,500 ft^3/s*	51–57 m^3/s *1,800–2,000 ft^3/s*	42–96 m^3/s *1,500–3,400 ft^3/s*	57–65 m^3/s *2,000–2,300 ft^3/s*
Average (40% of years)	43–68 m^3/s *1,500–2,400 ft^3/s*	57–74 m^3/s *2,000–2,600 ft^3/s*	51–119 m^3/s *1,800–4,200 ft^3/s*	65–79 m^3/s *2,300–2,800 ft^3/s*
Moderately Wet (20% of years)	68–79 m^3/s *2,400–2,800 ft^3/s*	62–79 m^3/s *2,200–2,800 ft^3/s*	77–133 m^3/s *2,700–4,700 ft^3/s*	74–91 m^3/s *2,600–3,200 ft^3/s*
Wet (10% of years)	79–85 m^3/s *2,800–3,000 ft^3/s*	68–85 m^3/s *2,400–3,000 ft^3/s*	91–133 m^3/s *3,200–4,700 ft^3/s*	79–108 m^3/s *2,800–3,800 ft^3/s*

Table 2. Change in stage (cm) of proposed Experimental Base Flows relative to midpoint of ranges in the Flaming Gorge Flow Recommendations (Muth et al. 2000) and the 1992 Biological Opinion for the Middle and Lower Green River (Kirk Lagory, Argonne, unpublished data).

Reach	Hydrologic Classification	Relative to Muth	Relative to Biological Opinion
Middle Green River (Reach 2)	Dry	21.61	18.35
	Moderately Dry	15.97	22.08
	Average	8.08	11.76
	Moderately Wet	-2.11	16.11
	Wet	-4.03	20.30
Lower Green River (Reach 3)	Dry	11.73	10.06
	Moderately Dry	8.99	12.19
	Average	4.79	6.92
	Moderately Wet	-1.28	9.60
	Wet	-2.53	12.19

Increases in base flows in dry years during the dry months of July through September will decrease summer drought stress, potentially allowing establishment of riparian vegetation, including invasive tamarisk at elevations just above the base flow level, on surfaces inundated by a discharge of roughly 51-85 m^3/s (1800-3000 ft^3/s) along the Middle Green River and 57-108 m^3/s (2000-3800 ft^3/s) along the lower Green River (Table 1). Similarity in base flows between years will help vegetation established in one year to survive in the following year, increasing the likelihood of long-term plant survival. This vegetation would increase fluid drag, reducing flow velocity, which would eventually lead to sediment deposition (Griffin et al. 2014). Elevated and stabilized baseflows should help to remove any vegetation below the new base flow level, resulting in a more pronounced lower vegetation boundary with a corresponding break in elevation. Decreases in duration or magnitude of peak flows would decrease the ability of the river to remove riparian vegetation, leading to further vegetation encroachment and sediment deposition. This would lead to steepening of side channel banks and a reduction in side channel area at flows just above the base flow level. Denser vegetation would resist flood erosion and rejuvenation of backwaters used by pikeminnow. As a result, the proposed flow modifications could benefit endangered pikeminnow in the short-term while degrading habitat for the same species in the long-term.

Options for mitigating effects of elevated base flows

The hydrologic options presented below could be used to reduce vegetative encroachment but would also affect other riverine resources not addressed here. Therefore, consideration of these options needs to be balanced against flow needs of other riverine resources.

1) In the wettest years, or in years where removal of young riparian vegetation is needed, relax the recommendations of the Larval Trigger Study Plan (2012) to maximize peak Green River flows by prescribing peak flows released from Flaming Gorge Dam to coincide with peak flows on the Yampa River. Alternatively, revisit current operational guidance for Flaming Gorge Dam spillway to allow releases greater than 244 m^3/s (8600 ft^3/s).
2) The proposed midsummer spike flows would remove some of the vegetation established as a result of elevated base flows.
3) In some drier years, reduce the base flows below the proposed values for some or all of the summer to desiccate and kill young riparian vegetation.

Effects of midsummer spike flows

Midsummer spike flows for controlling small-mouth bass would remove plant seedlings established earlier in the year at elevations between the stages corresponding to base flow and the spike peak. On the other hand, gradually declining flows following the spike could promote establishment of additional vegetation. Because these spike flows would occur relatively late in the season (July) they could promote invasive tamarisk, which releases seeds all summer. (In contrast native *Populus* and *Salix*, which release seeds in early summer, would not be likely to reproduce following midsummer spike flows). Furthermore, spike flows in one year could sub-irrigate roots of seedlings established above the stage of the spike in the current or previous years. Finally, water used for midsummer spike flows would not be available for spring peaks.

Options for mitigating effects of midsummer spike flows

1) Prescribe a discharge increase over time during the peak of the spike to minimize seedling establishment on moist recently deposited sediment.
2) Prescribe the declining limb on the spike flows to be as rapid as possible to desiccate seedlings established during or after the spike. The effectiveness of this prescription could decrease downstream because of the influence of uncontrolled tributary inputs downstream of Flaming Gorge Reservoir.
3) Prescribe some years without spike flows to avoid irrigating seedlings established in prior years.

Monitoring

The Recovery Program has requested elevated base flows and midsummer spike flows to promote survival of native fish and decrease survival of invasive fish in the Green River. The proposed changes could, however, degrade native fish habitat over the long-term. More specifically, the proposed flow changes, although modest in magnitude, could promote increased density of vegetation and sediment deposition on surfaces in the zone between the stage of base flows and just above the stage of spike flows. This sediment deposition could cause narrowing of the channel and side channels and subsequent changes in the morphology of backwater habitats used by age 0 Colorado pikeminnow. If such changes did occur, rapid detection would be important because (1) infrequent observations confuse the relation between hydrology and vegetation, (2) delay allows plants to grow, making them harder to remove, and (3) removal of larger plants requires higher flows whose magnitude is limited by dam configuration and current operational guidance, snow pack and downstream safety concerns. Meeting this need would require an adaptive management approach informed by annual monitoring, possibly including:

1) At 3-5 locations important for larval pikeminnow, annually acquire data from sets of channel cross sections measured with real-time kinematic gps, vegetation plots to assess change in density and species, and local aerial imagery acquired by drone. The cross sections and vegetation plots would provide high precision even under vegetative canopy, and the aerial imagery would provide broader-scale information on channel and vegetation change at the selected bars. These measurements could be made in early September to inform water management decisions for the following water year. To determine whether changes in vegetation or channel dimensions are related to elevated base flows, monitoring would need to take place in plots of known inundating discharge and inundation duration. To maximize effectiveness and efficiency, this monitoring would need to be integrated with ongoing vegetation monitoring along the Green River. Because tamarisk has played an important role in narrowing along the Green River, special attention could be paid to possible expansion of this species.
2) Every September collect rectified satellite imagery of the entire Middle and Lower Green River channel and floodplain with high enough resolution to detect bands of current-year vegetation. This need could be met in part using freely available sources.
3) Acquire digital elevation models of the entire Middle and Lower Green River channel and floodplain in early September using LIDAR from fixed-wing aircraft once every 5 years.

Monitoring carried out in the fall could be used to inform water management decisions the following spring in an adaptive management framework. For example, if monitoring reveals vegetation encroachment is occurring and snowpack is high, then the maximum feasible spring peak magnitude and duration could be prescribed to remove the vegetation. Alternatively, if snowpack is low, then base flows could be reduced to remove the vegetation by desiccation. Subsequent monitoring could be used to assess effectiveness of these strategies and to develop refinements.

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NPS 909/143192, March 2018

National Park Service
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Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525