Post-Dam effects on Geomorphology of the Green River

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ABSTRACT

Following the closure of Flaming Gorge Dam, geomorphic conditions along the Green River changed considerably. The lack of sediments from headwaters, decreased stream power downstream of Flaming Gorge Dam, and establishment of vegetation along river banks and sand bars has driven these changes in channel morphology. Just downstream of Flaming Gorge Dam, the erosion of fine sediments facilitates bed armoring. As sediment from tributaries enters the river system, channel aggradation becomes apparent primarily at the margins of the channel. Reduced peak flows and stability provided by vegetation prevent the erosion of sediments. The effects of Flaming Gorge Dam on channel narrowing can be assessed by studying geomorphically similar reaches above and below the confluence of the Yampa River, a large unregulated tributary. The Yampa River resets the Green River to more closely resemble pre-dam conditions.

INTRODUCTION

The Green River originates in the Wind River Range of southwestern Wyoming and continues south for over 700 miles before merging with the Colorado River near Moab, Utah. A myriad of geologic settings along the Green River play an important role in habitat variation, which has led to the evolution of many endemic species. Three dominant channel patterns along the Green River include debris fan-dominated canyons, fixed meanders, and restricted meanders. Debris fan-dominated canyons have steep canyon walls and numerous alluvial fans that can act to constrict the channel. Fixed meanders are confined to a deeply incised bedrock channel. Restricted meanders carve out their own channel in valley alluvium deposits, restricted only on the outside bends by resistant bedrock (Grams and Schmidt, 2002; Nichols, 2006, this volume). In addition to geologic constraints, a river's geomorphology also depends upon the hydrologic regime and sediment budget. Changes in a river's flow or sediment budget can occur naturally due to climatic variability or artificially due to human activities. After the Flaming Gorge Dam was constructed about 300 miles from the headwaters of the Green River, downstream channel characteristics changed considerably.

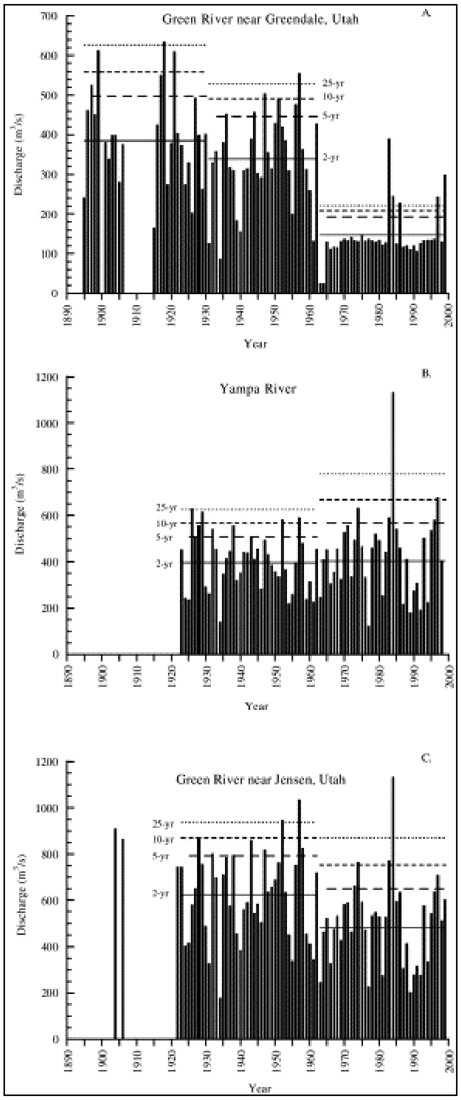
Prior to the construction of the Flaming Gorge Dam, the Green River channel characteristics depended for the most part on the natural flow regime, sediment supply, and bedrock geology. Sediments deposited during the Paleozoic and Jurassic were uplifted and eroded so that resistant rocks now characterize relatively straight and narrow canyons while soft bedrock creates low gradient, wide, meandering channels. Many side-canyons and tributaries have formed along fault planes or jointed bedrock where rocks were stressed and easily eroded. Most of the rivers sediment load originates from the semi-arid region of the lower Green River while most of the runoff originates from the headwaters (Andrews, 1986). Springtime melting events of the Rockies and headwaters of the Yampa provided high intensity peak flows to rework banks along the tributaries and main stem. These high peak flows were able to erode channel banks and entrain more sediment, increasing turbidity and bedload.

Following the construction of the Flaming Gorge Dam, flow characteristics of the Green River changed dramatically. Sediments were trapped behind the dam, starving the channel just downstream. Flow regulation increased base flows and decreased the intensity of high flows, influencing the river's ability to erode sediments downstream. A decrease in the amount of sediments from upstream along with the decrease in erosive capability downstream has led to bed armoring, channel narrowing, an increase of fine sediments along banks and gravel bars, and vegetation establishment on banks.

DAMS AND THE SERIAL DISCONTINUITY CONCEPT

Rivers reach a state of quasi-equilibrium after decades to centuries of adjustment. This quasi-equilibrium state is defined as having no net accumulation or depletion of sediment in the bed, banks, or floodplain and nearly constant average hydraulic characteristics (width, depth, velocity, roughness, slope, and channel pattern) through a reach of channel at a given discharge (Andrews, 1986). Modifications in the natural flow regime can drive morphological changes in channel form, disrupting the existing quasi-equilibrium state (Petts and Gurnell, 2005).

The magnitude of flood events can be reduced by dams that alter seasonal variability (Petts and Gurnell, 2005). The Flaming Gorge dam reduces spring peak flows while increasing summer base flow. Flow regulation can affect different locations along a river in different ways, depending on reach characteristics. Aggradation may occur in slow moving, wide channel reaches while degradation can occur in the faster moving, narrow channel reaches. Also, cycles of erosion and sedimentation at one location may occur while the channel is adjusting to changes (Wolman, 1967). As distance downstream increases, the river progressively reverts to natural conditions, especially as tributaries downstream from dams add unregulated flows to the main stem (Stanford and Ward, 2001). However, geomorphic adjustments do not always follow this model. Even with well-researched geomorphic and flow characteristics, channel adjustments below dams are difficult to predict (Petts and Gurnell, 2005).



BED ARMORING

Prior to the construction of Flaming Gorge Dam, the Green River was most likely in a state of quasi-equilibrium. High flows washed out sediments that were deposited along banks and the floodplain. Although these processes varied with climate, seasonal and even annual modifications in channel morphology, these natural variations did not compare to the changes forced by Flaming Gorge Dam. Just below the dam, the water’s sediment load is in deficit. All the sediments carried from the river’s headwaters are trapped behind the dam (Grams and Schmidt, 2002). One would expect the channel below the dam to incise, a common process that occurs when sediment load is decreased and stream power is maintained. Along the Green River, the bed has not degraded at any location where historical data is available (Grams and Schmidt, 2005). Instead of degradation, bed armoring has occurred just downstream of Flaming Gorge Dam. Following the closure of the dam, clear waters stripped away the finer sediments but were unable to transport larger clasts deposited by pre-

Figure 1. (above) **A**. Annual maximum discharge at Greendale gage. Utah. **B**. Annual maximum discharge along the Yampa River. **C**. Annual maximum discharge at Jensen gage. Utah. (Grams and Schmidt, 2002)

dam high flow events and debris-flows. As a result, bed armoring instead of incision is apparent just below the dam.

CHANNEL AGGRADATION & NARROWING

Especially within sand-bedded, semi-arid streams, flood regulation promotes channel aggradation (Schumm and Hadley, 1967). Studies completed by Grams and Schmidt (2002) confirm aggradation along the Green River below Flaming Gorge dam. Fine sediments have accumulated along riverbanks and gravel bars in the absence of high intensity flows. Before Flaming Gorge dam was built, peak flows could reach above the main channel to erode fine sediments. After the completion of Flaming Gorge dam in 1962, the hydrologic flow regime changed dramatically. Figure 1, as presented by Grams and Schmidt (2002), shows the annual maximum discharge of the Green River at significant localities in relation to Flaming Gorge dam. Figure 1a illustrates the differences between the pre-dam and post-dam annual maximum discharges at the Greendale gage just below Flaming Gorge dam (see Figure 2 for specific localities). Here a significant difference in the annual maximum discharge exists between pre-dam and post-dam periods. During the post-dam period, flows rarely exceeded the power plant capacity of 130 m^3/s (4,590cfs). Figure 1b describes the maximum annual discharge along the Yampa River. Except for the large flood event in 1984, no significant difference is apparent on the annual maximum discharge time-series of this unregulated river. Figure 1c describes the annual maximum discharge along the Green River at Jensen gage below the confluence of the Yampa. Here, a discernable difference exists between the pre-dam and post-dam annual maximum discharge time-series. The 2-year, 5-year, 10-year, and 25-year recurrence flows all occur at lower discharges. Even so, the difference between the pre-dam and post-dam annual maximum discharge at Jensen gage is greatly subdued in comparison to the Greendale gage (Grams and Schmidt, 2002). These graphs demonstrate the restoration of pre-dam hydrology as distance downstream from Flaming Gorge dam increases. Conversely, the restoration of the natural flow regime as distance downstream from Flaming Gorge dam increases does not directly correlate with the geomorphic alterations in respect to their distance downstream of the dam. Channel narrowing downstream of Flaming Gorge dam depends on the degree of reduced peak flows, sediment supply, and local geomorphic conditions (Grams and Schmidt, 2005).

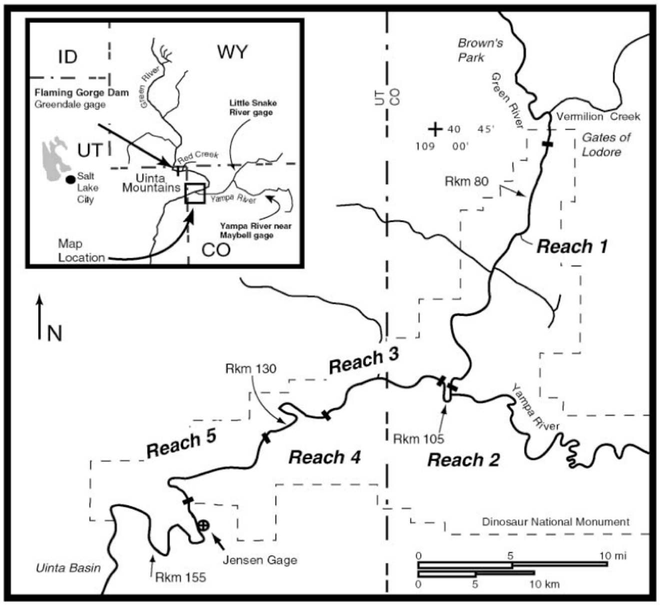


Figure 2. (above) Map showing the locations of Greendale and Jensen gages and the along the Green River and the Yampa River in relation to Flaming Gorge dam. (Grams and Schmidt, 2002)

Studies conducted by Andrews (1986), Lyons et al. (1992), Merritt (1997), Allred and Schmidt (1999), Grams and Schmidt (2002), and Grams and Schmidt (2005) all report channel narrowing along the Green River downstream of Flaming Gorge Dam. Reduced peak flows allow fine sediments to accumulate on river banks, channel islands, and floodplains. Generally, in debris fan-dominated canyons and gravel-bedded restricted meandering reaches, active gravel beds have become inactive and are accumulating fine sediments. Channel narrowing in restricted meandering and fixed meandering reaches is occurring by vertical accretion of sediment on channel banks and previously active side-channels (Grams and Schmidt, 2005). Within sand-bedded restricted meandering reaches, new islands are forming and existing islands are growing larger (Grams and Schmidt, 2002). Adjustments due to a combination of deposition of post-dam sediment and stabilization of pre-dam deposits, has resulted in a 10-30% reduction in average channel width (Grams and Schmidt, 2005). Although average discharge depends on distance downstream of Flaming Gorge Dam, the degree of post-dam channel narrowing depends on the geology and flow characteristics within each reach.

Grams and Schmidt (2002) found that aggradation in debris-fan dominated canyons was proportional to stream power below Flaming Gorge Dam; as stream power decreased, aggradation increased. These canyons include Red Canyon, Lodore Canyon, Whirlpool Canyon, and Split Mountain Canyon where average slope is higher, channels are narrower, and more debris fans are present than in fixed or restricted meander reaches. Within these canyons, aggradation has occurred on pre-dam active gravel bars and new islands have formed. Vegetation has become established on what was bare sand before the closure of Flaming Gorge Dam (Grams and Schmidt, 2002). Narrowing in Red Canyon was low (10%) due to the proximity to Flaming Gorge Dam and high stream power (Grams and Schmidt, 2005). In debris fan-dominated canyons downstream from the Yampa River confluence, narrowing was not as prominent as in Lodore Canyon, just above the Yampa River confluence (Grams and Schmidt, 2002). Narrowing in Lodore Canyon was about twice that of Whirlpool Canyon and Split Mountain Canyon (Grams and Schmidt, 2002). This suggests that the confluence of the Yampa River resets the flow regime, increasing stream power and dampening the effects of Flaming Gorge Dam.

Fixed meanders are confined by bedrock and include Swallow Canyon, Swinging Bridge Canyon, and Echo Park. Restricted meanders form in easily eroded, alluvial valleys and include Browns Park and Island Park. Within these reaches, specific stream power was not significantly altered by flow regulation and narrowing occurred by bank deposits, island and gravel bar growth and vegetation establishment as it had prior to the closure of Flaming Gorge Dam (Grams and Schmidt, 2002).

SEDIMENT BUDGET

The change in sediment load has been recorded at different gaging stations along the Green River. One model by Grams and Schmidt (2005) attempts to predict change in sediment storage by adding up sediment influx of tributaries and subtracting the efflux. Tributary locations along the Green River are illustrated in Figure 3 from Andrews (1986).

$$I_{GRG}+I_{RC}+I_{VC}+I_{YR}+I_{ugt} = \Delta S + E_{GRJ}$$

I_{GRG} = Influx at Greendale gage

I_{RC} = Influx at Red Canyon

I_{VC} = Influx at Vermillion Creek

I_{YR} = Influx at Yampa River

I_{ugt} = Influx at ungaged tributaries

E_{GRJ} = Efflux at Jensen gauge

ΔS = Changes in storage

At the completion of their study, Grams and Schmidt (2005) recognized this sediment budget to be indeterminate. Reasons for uncertainty in this and other sediment budgets comes from uncertainties in sediment sampling, the variability of tributary influx (especially in arid and semi-arid alluvial rivers), and unavailable detailed transport data (Grams and Schmidt, 2005). There are zones of accumulation but it is difficult to predict the location and the magnitude of change. Even though the sediment budget was described as indeterminate, it is known that the sediment budget is no longer in a state of quasi-equilibrium. A detailed sediment budget of aggradation and sediment entrainment along the Green River was not determined although average sediment loads before and after the construction of Flaming Gorge Dam were estimated. Measurements of suspended sediments were used to determine the average annual load at Jensen. Annual suspended sediment loads were shown to decrease by 57% using information averaged for the 14 year period before the closure of Flaming Gorge Dam and the 16 year period after the closure of the dam (Grams and Schmidt, 2002).

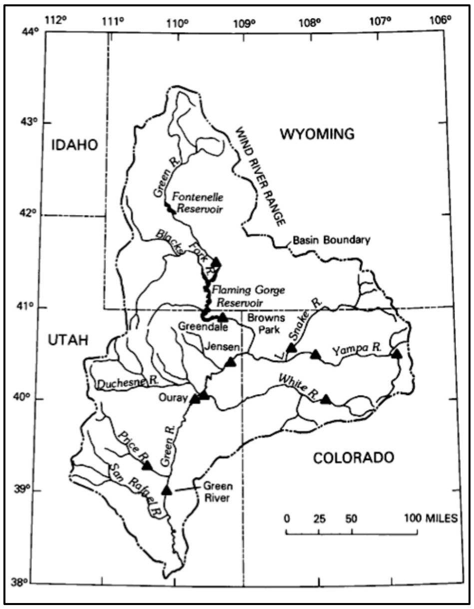
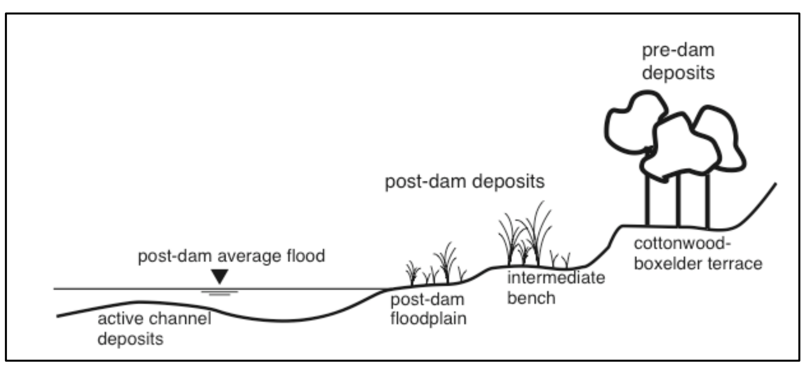


Figure 3. (left) Map of Green River tributaries and gaging stations. (Andrews, 1986)

FLOODPLAIN FORMATION

Terraces on the floodplain of the Green River form as a result of vertical accretion of sedimentary deposits of alternating flood stages (see Figure 4 for illustration). The establishment of vegetation further promotes the stability of these terraces. Prior to the construction of Flaming

Figure 4. (right) Sketch of floodplain terraces corresponding to pre-dam and post-dam flood levels and vegetation establishment. (Grams and Schmidt, 2005)



Gorge Dam, large floods of 550 m^3/s (19,420 cfs) with an approximate pre-dam recurrence interval of 25 years formed the cottonwood-box elder terrace (c-b terrace). During inundation, the c-b terrace stratigraphy was constructed by the deposition of sand, silt and clay. This floodplain has not been inundated since the dam was built and has been taken over by cottonwoods and box elders. The 5-year post-dam flood occurs within the range of 240 to 300 m^3/s (8,474 to 10,593 cfs, respectively) and deposits sediments along the intermediate bench. Prior to the closure of Flaming Gorge Dam, this floodplain was inundated every 2 years on average. The reduction in flood events of this magnitude may be one factor aiding the encroachment of vegetation such as tamarisk (*Tamarix ramosissima)* onto the intermediate bench (Grams and Schmidt, 2002). The post-dam floodplain is now inundated annually and has an average elevation of 1.1 m below the intermediate bench (Grams and Schmidt, 2002). Tamarisk, willow, and young cottonwood riparian vegetation has been established on the post-dam floodplain in some locations (Grams and Schmidt, 2002).

VEGETATION

Along the Green River downstream of Flaming Gorge Dam, decreased high erosive flows and elevated base flows have promoted deposition of fine sediments along banks allowing vegetation establishment and facilitating channel narrowing. Riparian vegetation increases bank stability, inhibiting erosion and enhancing sedimentation and floodplain formation (Friedman et al., 1996). From 1930 to 1940, before Flaming Gorge dam was built, average peak flows were low allowing for the first episode of channel narrowing and vegetation establishment (Grams and Schmidt, 2005). The introduction of tamarisk, an invasive species with a very strong root system, coincided with this period (Grams and Schmidt, 2005). Tamarisk roots can stabilize banks and lead to aggradation of gravel bars. With the continued low peak flows after the closure of Flaming Gorge Dam, increased vegetation along banks and islands has coincided with increased channel narrowing. The reduction in frequency of floods and increased base flows enhance conditions favorable for vegetation growth. Moisture from elevated base flow and the reduction in flood disturbances provide these conditions (Petts and Gurnell, 2005). Along one reach of the Green River, Merritt and Cooper (2000) stated that within 10 years of the closure of Flaming Gorge dam, nearly 90% of the previously active point bar surfaces had been colonized by riparian vegetation and the average channel width had been reduced by 13% (19m). This positive feedback cycle of increased bank stability by vegetation and aggradation will likely continue unless a change in peak flows and vegetation removal is implemented. It is unknown whether the new hydrologic regime or the establishment of vegetation is responsible for the majority of channel adjustments. Most likely, the combination of reduced peak flows and bank stability by vegetation has led to channel narrowing.

CONCLUSIONS

Along the Green River, changes in sediment and water discharge have significant impacts on the geomorphology of the channel. These morphological drivers have been influenced by the Flaming Gorge Dam. Downstream of Flaming Gorge Dam, sediment is lacking and stream power has decreased. This allows bed armoring to occur immediately below the dam and sediment to accumulate in other reaches. Geomorphic changes are not only tied to the distance downstream from Flaming Gorge Dam but also to reach-specific geology. Overall, channel width has decreased from 0 to 10% within canyons dominated by debris-fans and fixed meanders and up to 27% within restricted meanders (Grams and Schmidt, 2005). Vegetation has intensified channel narrowing. Below the confluence of the Yampa River, the addition of non-regulated flows has helped reset conditions to resemble post-dam hydrologic and geomorphic conditions.

New flow regulations implemented to improve habitat for endangered fishes may help further restore pre-dam geomorphic conditions (Muth et al., 2000). Baseflows reflecting the natural response to annual precipitation should work to enhance habitat conditions for native fishes (Muth et al., 2000). Lower base flows should discourage vegetation on banks allowing higher peak flows to wash out fine sediments that have accumulated on channel banks and bars. This would help create clean spawning habitats for some fish species (Muth et al., 2000). Higher peak flows will increase backwater habitat used by both native and non-native fishes. During dry years, reduced habitat space should negatively affect both native and non-native fishes, but the increased water temperatures should lower the numbers of non-natives, reducing competition. The combination of geomorphic alterations and flows may lead to increased survival of native endangered fishes over the long term.

REFERENCES

Allred, T.M., Schmidt, J.C., 1999. Channel narrowing by vertical accretion along the Green River near Green River, Utah. Geological Society of America Bulletin 111: 1757-1772.

Andrews, E.D. 1986. Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah. Geol. Soc. of Amer. Bull., vol. 97, p. 1012-1023.

Friedman, J.M., Osterkamp, W.R., Lewis, W.M., 1996. The role of vegetation and bed-level fluctuations in the process of channel narrowing. Geomorphology 14, 341-351.

Grams, P.E., Schmidt, J.C. 2005. Equilibrium or indeterminate? Where sediment budgets fail: Sediment mass balance and adjustment of channel form, Green River downstream from Flaming Gorge Dam, Utah and Colorado. Geomorphology 71 (2005) 156– 181.

Grams, P.E., Schmidt, J.C. 2002. Streamflow regulation and multi-level flood plain formation: channel narrowing on the aggrading Green River in the eastern Uinta Mountains, Colorado and Utah. Geomorphology 44 (2002) 337-360.

Lyons, J.K., Pucherelli, M.J., Clark, R.C., 1992. Sediment transport and channel characteristics of a sand-bed portion of the Green River below Flaming Gorge Dam, Utah. Regulated Rivers: Research and Management 7, 219-232.

Merritt, D.M., Cooper, D.J., 2000. Riparian Vegetation and channel change in response to river regulation: a comparative study of regulated and unregulated streams in the Green River Basin, USA. Regulated Rivers: Research and Management 16, 543-564.

Merritt, D.M., 1997. Riparian vegetation and geomorphic features on regulated and unregulated rivers: Green and Yampa, NW Colorado, *Unpublished M.S. Thesis*, Colorado State University, Fort Collins, CO. 65pp.

Muth et al., 2000. Flow and temperature recommendations for endangered fishes in the Green River downstream of Flaming Gorge Dam. Final Report to Upper Colorado River Endangered Fish Recovery Program, Denver.

Petts, G.E., Gurnell, A.M. Dams and Geomorphology: Research progress and future directions. Geomorphology 71 (2005) 27– 47.

Schmidt, J.C. 2005. The Colorado River. Department of Aquatic, Watershed, and Earth Resources, Utah State University.

Schumm, S.A., Hadley, R.F., 1967. Arroyos and the semi-arid cycle of erosion. Am. J. Sci. 263, 110-119.