Serial Discontinuity Concept Applied to the Hydrology of the Green River

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ABSTRACT

The natural flow regime of the Green River, from Flaming Gorge Dam to the mouth of the Colorado River, has been altered since dam closure in November 1962. The pre-dammed river system had extremely high late-spring to early-summer peak floods originating from snowmelt and relatively low baseflows during summer, autumn and winter (Muth et al 2000). Different eras of dam operation have had different effects on the natural flow regime. From closure to 1992, dam managers released water based on electricity demand, resulting in a highly unnatural flow regime. Profound changes to the natural hydrograph included the loss of high late-spring/early-summer peak floods and a change to higher than natural base flows. Many fish species in the Green River system are endemic, having evolved lifecycles dependent upon the characteristics of the natural flow regime. Several native fish in the river system became endangered, mainly as a result of Flaming Gorge Dam operations. From 1992 to 2005, Flaming Gorge Dam was operated under the Biological Opinion, which provided flow and temperature recommendations necessary for endangered fish recovery, while still meeting power generation and irrigation demands. The overall goal of the Biological Opinion was to create a flow regime resembling, as close as possible, the natural flow regime. Truly natural flow can never be achieved because of hydraulic limitations of Flaming Gorge Dam, diversions for irrigation, and the added hydrologic effects of other dams in the Upper Colorado watershed (Muth et al 2000). The serial discontinuity concept (SDC) was applied to the hydrology of the Green River from Flaming Gorge Dam to the Green River gaging station. Beginning in 1992, more natural flows have been observed at the USGS stream-flow gage near Jensen, UT and the gage near the town of Green River, UT. Since more natural flows have been observed, the hydrologic discontinuity distance has decreased. The success of the Biological Opinion flow recommendations will be judged according to the long term population trends of the endangered fish.

INTRODUCTION

In the West, reservoir storage and water distribution systems are engineering marvels. For example, some historians would argue that the Colorado River Storage Project, and more specifically Hoover Dam, is on the same level as the Pyramids of Giza, the Roman Coliseum, and the Great Wall of China. In the golden-era of dam construction, nearly every major river in the West was dammed or diverted to benefit humans in one way or another. With protection from floods, cheap and clean electricity, and a stabilized supply of agricultural water, dams seemed to be great investments. Taming the Colorado River and other western rivers made it possible to settle and irrigate semi-desert areas that would be inhospitable otherwise. For example, the city of Las Vegas and the multi-million dollar agricultural business of Imperial Valley would not exist without the Colorado River Storage Project. However, the benefits associated with development of western watersheds, were not without environmental consequences.

In the past four decades, concern over environmental issues related to dam operations has become more pronounced. The environmental effects of dams can be severe because they influence two primary factors that determine the overall morphology of a river: water and sediment (Grant et al. 2003). Changing the overall morphology of a river can have profound effects on the native biota of a watershed. Furthermore, dams can impact other important aspects of the system including fish migration, inundation patterns, and the timing and magnitude of peak flood pulses. In general, dams that alter the natural flow and temperature regime have adverse effects on the native biota. Flaming Gorge Dam is no exception; several native fish species are currently threatened with extinction. These species include the Colorado pikeminnow, the bonnytail chub, the humpback chub and the razorback sucker (Muth et al. 2000). Since these unique fish species are found only in the Colorado River watershed, they have tremendous intrinsic value. According to the U.S. Fish and Wildlife Service, efforts to save these particular fish from extinction have resulted in the spending of more than eighty-one million dollars from 1989 to 2000. Many of these efforts have been focused on the Green River system in Utah and Colorado, because this river system is one of the last remaining places where these endangered fish are found (Muth et al. 2000). While many factors, including nonnative plant and fish species, might have led to a decline in the native fish species, the major perturbation to the natural system has been Flaming Gorge dam.

Since Flaming Gorge reservoir began to fill in 1962 and became fully operational in 1967, there have been 2 major eras of dam operations: 1962 to 1992, and 1992 to present day. In general, Flaming Gorge Dam has been operated to provide maximum power revenue while maintaining a full reservoir and avoiding the use of the bypass tubes and spillway (Muth et al. 2000). From 1962 to 1992, releases from the dam were highly unnatural. These unnatural releases are blamed for the alteration or loss of native fish habitat, resulting in a decline of their populations. From 1992 to present, Flaming Gorge Dam has been managed in a way to restore the natural flow regime as best as possible, while still meeting power-generation and other demands (Muth et al. 2000). The overall goal of adjusting dam releases has been to improve habitat and enhance populations of the endangered fishes (Muth et al. 2000). The success of efforts since 1992 will be determined by assessing the long term population trends of the endangered fish.

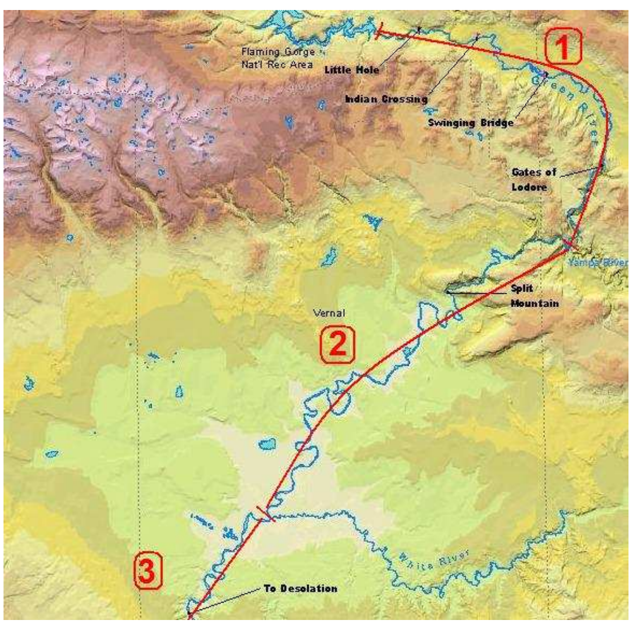
Quantitatively evaluating the recovery of the Green River's natural flow regime can be assessed by comparing the natural hydrograph to the current hydrograph. One concept, known as serial discontinuity, facilitates this comparison. The serial discontinuity concept explains how rivers have an innate tendency to restore natural conditions, as distance downstream from dams or other obstructions increases (Stanford and Ward 2001). In this context, the hydrologic discontinuity distance is the distance downstream from the dam at which the river restores its natural flow regime. Restoration of the natural flow regime is facilitated by the inputs of unregulated tributaries that lessen the hydrologic effects of the dam. Evaluating the recovery of the natural flow regime can be accomplished by comparing the hydrologic discontinuity distance during 1962-1992 to the hydrologic discontinuity distance from 1992 on. While efforts have been made since 1992 to shrink the hydrologic discontinuity distance, there are certain limitations that prevent total restoration.

SOURCES AND DEPLETIONS OF THE GREEN'S WATER

At a length of 764 miles, the Green River occupies a total area of 44,700 square miles. The sources of the Green River are the mountainous regions of western-central Wyoming, which have maximum elevations of roughly 14,000 ft. These mountainous regions include the Wind River and Wasatch Mountain Ranges, which average over 40 inches of precipitation each year. The snowpack melts in late spring to early summer, producing heavy runoff and peak flow rates in the Green River watershed. The spring peak flows are easily distinguishable on the natural hydrograph at any gage in the watershed because 70% of the total annual volume of the Green River is derived from snowmelt (Muth et al. 2000). Furthermore, climate varies considerably in the Green River basin. For example, lower semi-arid regions, which make up the majority of the basin, average less than 10 inches of precipitation each year (Muth et al. 2000).

The primary reason for the construction of reservoirs in the watershed has been to meet the demands of irrigation and power generation. Estimated 1998 irrigation depletions in the Upper Green and Yampa watersheds are 460,000 acre-ft and 187,000 acre-ft, respectively (Muth et al, 2000). Other depletions result from evaporation as well as municipal and industrial uses. Total annual volumes passing though the USGS streamflow gage near Green River, UT from 1906 to 1929 averaged 5,710,000 acre-ft and from 1930 to 1996, averaged 4,047,000 acre-ft. This 29% decrease in total annual volume is largely explained by climate change and to a lesser extent, irrigation diversions and other depletions (Muth et al. 2000). The effects of irrigation and other depletions on annual volumes are significant, but much less than the historical hydrologic effects of Flaming Gorge Dam. Flaming Gorge Reservoir, the largest reservoir in the watershed, is capable of storing roughly twice the annual inflow, with a peak capacity of 3,749,000 acre-ft (Muth et al. 2000).

When discussing flows of the Green River, it is important to know the locations of relevant gages and the three different reaches. The following map, Figure 1, shows the different reaches used in this report and other Green River related documents. Flow in the Yampa River is measured in Dinosaur National Monument, just upstream from its Confluence with the Green River, at the USGS gage near Deerlodge Park, CO.



Reach 1: Flaming Gorge Dam to the Yampa River confluence. Streamflow data is measured at the USGS gage near Greendale, UT, directly below the dam. (river mile 345 to 410)

Reach 2: Yampa River Confluence to White River Confluence. Streamflow data is measured at the USGS gage near Jensen, UT. (river mile 246 to 345)

Reach 3: White River Confluence to Colorado River. Streamflow data is measured at the USGS gage near Green River, UT. (river mile 0 to 246)

Map from Bureau of Land Management - Vernal Field Office 2006

Figure 1. Map showing the three study reaches of the Green River

THE NATURAL FLOW REGIME

Before Flaming Gorge Dam closure in 1962, the Green River was a wild river that produced high spring flows and low base-flows. Although there were dams in the Upper Green basin during 1950 to 1962, they were relatively small and had little effect on the natural hydrology. During this period of record, the only notable reservoir in the Upper Green watershed was Big Sandy reservoir, which has a maximum capacity of only 383,000 acre-ft. In general, smaller reservoirs have less potential to modify the natural flow pattern (Muth et al. 2000). Therefore, the hydrograph from 1950 to 1962 (Fig. 2) closely resembles the natural hydrograph.

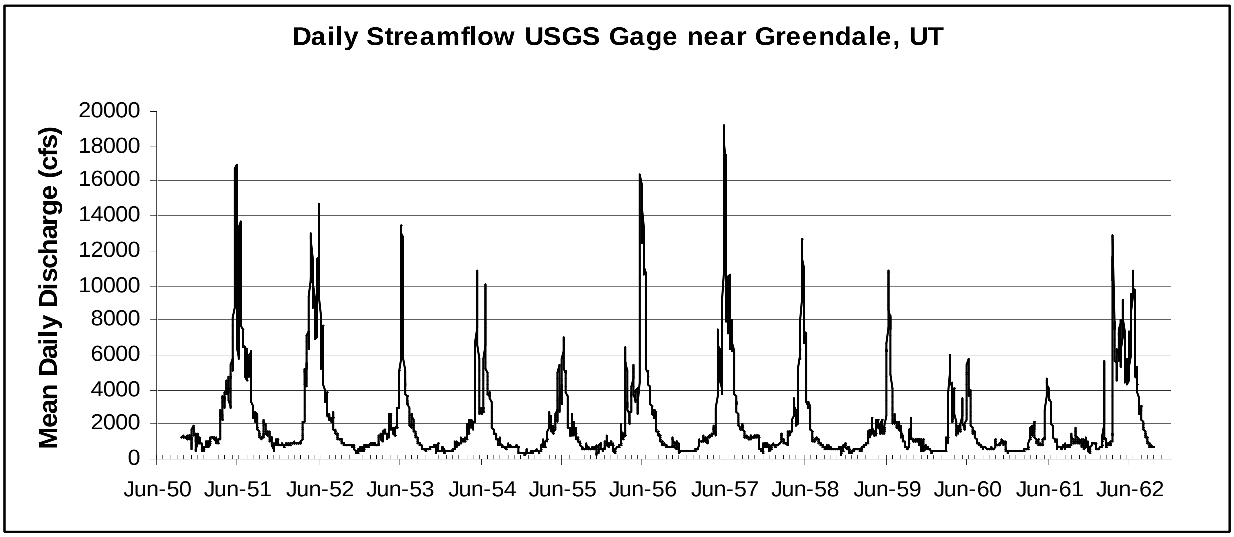


Figure 2. Daily Mean Stream Flow (1950-1962) at Greendale, UT Gage (USGS, 2006)

USGS stream-flow measurements taken over the period of record reveal the extreme variability of the natural river hydrology. Peak flows at the Greendale gage are estimated to have exceeded 20,000 cfs in 1899, 1918, and 1921. Floods of this extreme magnitude no longer occur probably as a result of climate change (Schmidt 1994). Before construction of Flaming Gorge Dam, the mean annual peak flow was roughly 11,600 cfs at the Greendale gage (Muth et al. 2000). The pre-dam peak flows occurred roughly during the first weeks of June. Prior to dam closure, the river near the Greendale gage was covered by ice for 3 to 5 months per year. The last year ice-cover was reported was 1958 (Schmidt 1994). Ice-formation was a result of extremely low temperatures and flows during winter months. Base flows at Greendale and other gages are generally low once snowmelt runoff has ceased.

The Yampa River drains the north-east portion of Colorado and eventually joins the Green River sixty-five miles below Flaming Gorge Dam. The Yampa is the largest tributary to the Green and has the largest influence the Green's hydrograph. On average, 48% of the flow at the Green and Yampa confluence originates from the Yampa River (Muth et al. 2000). Little regulation occurs in the Yampa watershed and the current hydrograph closely resembles the natural hydrograph. Melting snowmelt provides extremely high peak floods which generally occur in late May (Muth et al. 2000). The 1982 to 1992 Yampa River hydrograph (Fig. 3) is very similar to the unregulated Green River hydrograph (Fig. 2).

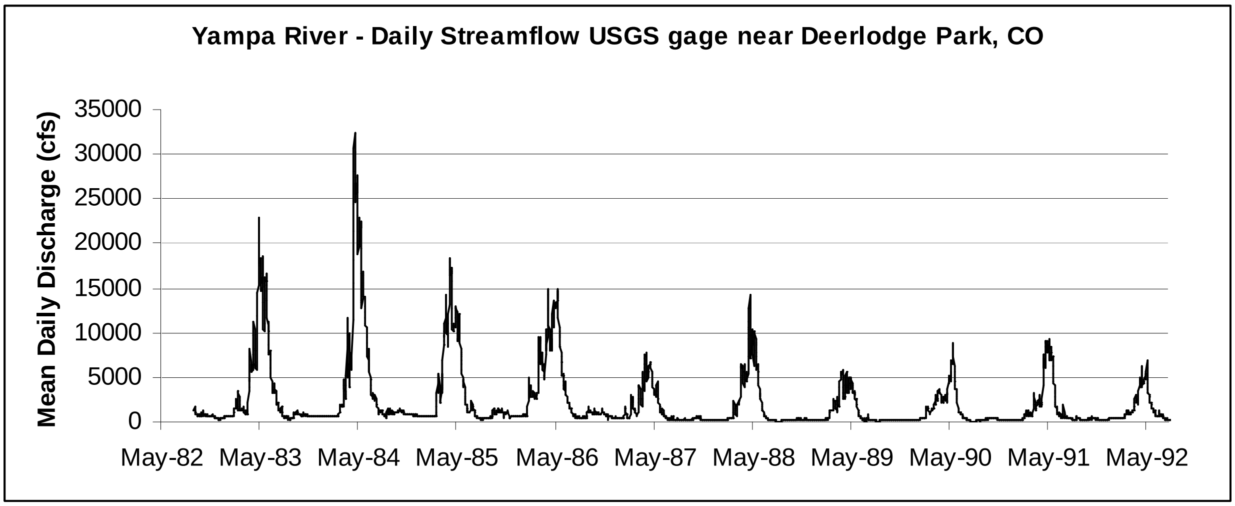


Figure 3. Yampa River Daily Mean Streamflow 1982-1992 at Deerlodge Park, CO Gage (USGS, 2006)

At the Jensen gage, flow from the Yampa River is combined with flow from the Green River. From 1947 to 1962, the mean annual peak flow at the USGS gage near Jensen, UT was roughly 24,000 cfs. Figure 4 shows peak flows at the Jensen gage from 1947 to 1996, with the contributions from the Green and Yampa rivers indicated. Prior to closure of Flaming Gorge Dam in 1962, peak flows in the Green and Yampa rivers were similar in magnitude and duration (Muth et al. 2000). Figure 4 also shows the drastic year to year variability of peak flows. The high level of variability of peak flows makes it difficult to compare pre- and post-dam flows to illustrate the effects of Flaming Gorge (Muth et al. 2000).

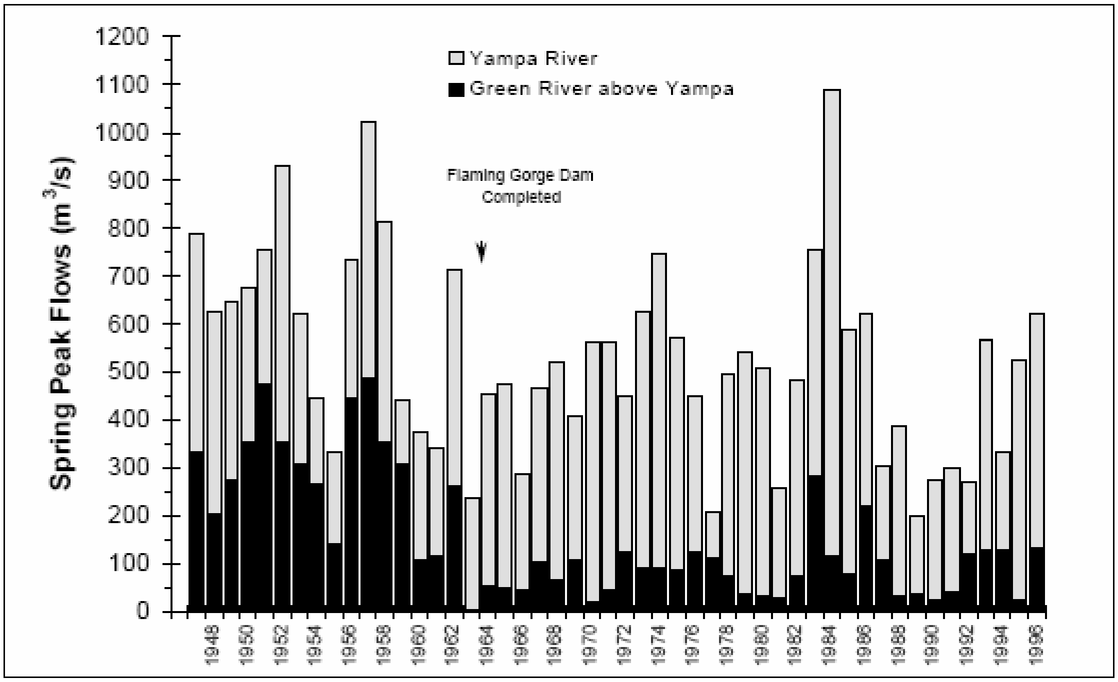


Figure 4. Peak flow rates at USGS gage near Jensen, UT. 1947-1996 (Muth et al. 2000)

Before Flaming Gorge Dam closure in 1962, annual peak flows at the USGS gage near Green River, UT averaged 32,700 cfs. Peak flow exceeded 60,000 cfs in 1897, 1909, 1917, and 1921 (Schmidt 2004). The highest peak flow at the Green River gage was 68,000 cfs on June 27, 1917. The lowest peak of 6,459 cfs occurred on May 17, 1934 (Muth et al 2000). Once again, a drastic level of peak flow variability exists in the natural flow regime. At the Green River gage, the natural flow regime produced relatively low baseflows once the snowpack was finished melting.

The Colorado pikeminnow, humpback chub, bonytail chub and razorback sucker all have developed life-cycles dependent upon the natural flow regime of the Green River. In general, these endemic species rely on large peak floods to create habitat outside the river channel. High flows also scour out and reshape sediment deposits inside the river channel, producing certain conditions necessary for spawning (Muth et al 2000). The natural Green River system was a harsh environment for fish. Only highly specialized fish could survive the extremely variable conditions. Before the construction of Flaming Gorge Dam, native fish were more prominent throughout the watershed. The next section will explain exactly how the natural flows of the Green have been changed as a result of Flaming Gorge Dam operations.

DAM OPERATIONS 1962 to 1992

Flaming Gorge Dam releases are limited by physical properties of the spillway, bypass tubes, and power generation turbines. The maximum release during full power generation is approximately 4,800 cfs. Two bypass tubes, which do not produce electricity when in use, have a maximum capacity of approximately 4,000 cfs. During extremely large floods, water can flow through the spillway tunnel at a rate of roughly 28,000 cfs. Since closure, the spillway has only been used twice.

From 1962 to 1966, Flaming Gorge Dam held back as much water as possible in order to fill the reservoir to the required height for power generation. During this time, releases from the dam were extremely low (see Fig. 5) (Muth et al. 2000). From dam closure to 1978, peak releases from the dam never passed power plant capacity of 4,800 cfs. The magnitude of the annual peak discharge of the Green River at the Greendale gage decreased about 60% after construction of Flaming Gorge Dam was finished (Schmidt 1994). The 1955 to 1975 hydrograph (Fig. 5) clearly shows the alteration of the Green River's natural flow regime at the Greendale streamflow gage. Before 1962, the Green saw spring peak flows averaging 11,600 cfs. After 1962, the daily discharge rarely passed full power generation capacity of 4,800 cfs.

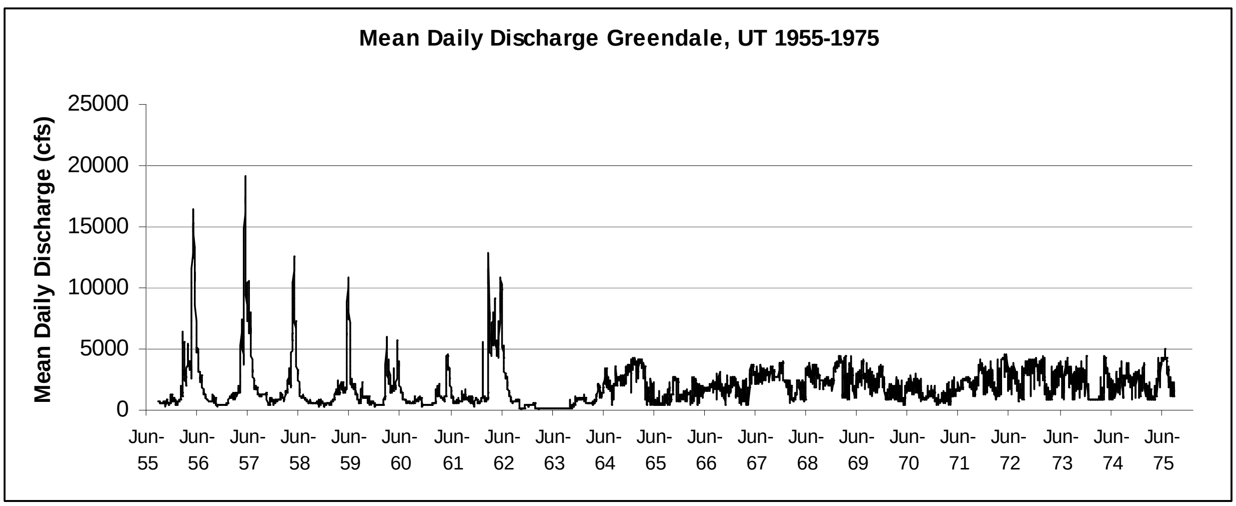


Figure 5. Daily Mean Streamflow (1967-1978) Greendale Gage (USGS, 2006).

In order to meet electricity and irrigation demands, dam managers released uniform monthly volumes. Figure 6, the mean monthly flow at the Greendale gage, further shows the alteration of the natural flow regime. Unregulated flow produced relatively low monthly flow except during spring runoff. The greatest mean monthly flow occurs during June in the unregulated flow regime. Mean monthly flow after completion of Flaming Gorge Dam is uniform, and during certain months, much higher than unregulated flow.

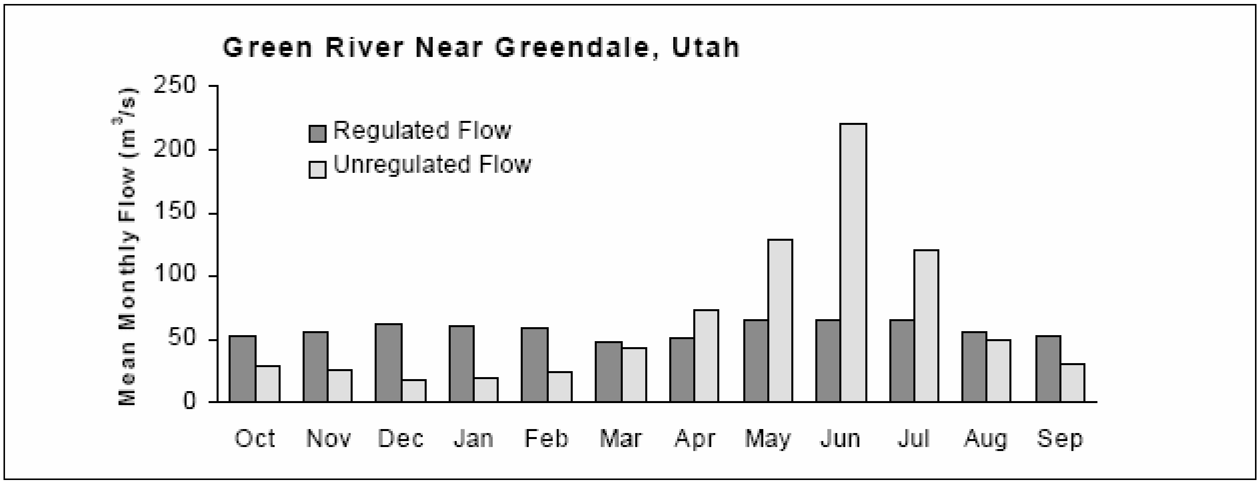


Figure 6. Mean Monthly Discharge – Regulated vs. Unregulated at Greendale Gage (Muth et al. 2000)

Figure 7 shows mean daily flow at the gage near Jensen, UT. The effects of Flaming Gorge Dam on the natural flow regime further downstream in reach 2 are less apparent, yet significant. From 1947 to 1962, the mean annual peak flow at the Jensen gage was 24,000 cfs. From 1963 to 2000, the mean annual peak flow was reduced to 17,400 cfs (Muth et al. 2000). While it might not be obvious on the Jensen hydrograph, the changes to peak flow have been 25% (Schmidt 1994). Furthermore, average regulated baseflows are nearly double the average unregulated baseflows.

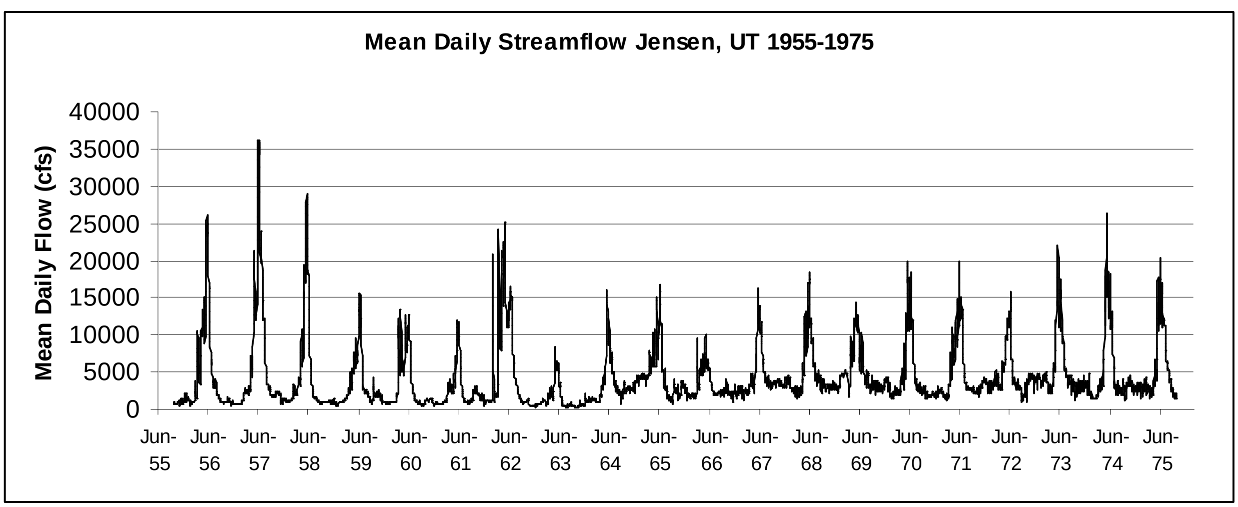


Figure 7. Mean Daily Streamflow Jensen Gage (1955-1975) (USGS, 2006)

Comparing the unregulated and regulated mean monthly flow (Fig. 8) further shows the alteration to the natural flow regime at the Jensen gage. Regulated flows are not uniform throughout the year because of the natural flow characteristics of the Yampa River. In other words, the Yampa River acts as a restorer of the natural flow regime at the Jensen gage.

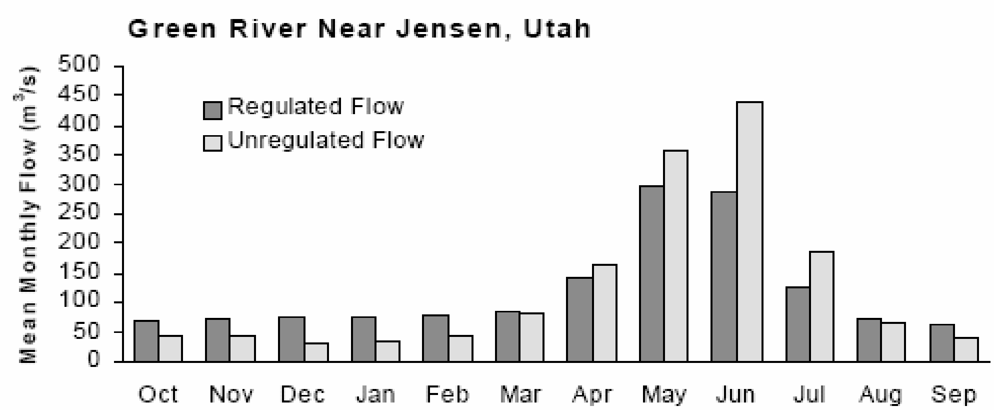


Figure 8. Mean Monthly Discharge-Regulated vs. Unregulated at Jensen Gage (Muth et al. 2000)

The following table summarizes the changes to the natural flow regime at the 3 different gages. Flaming Gorge Dam has resulted in a reduction of mean monthly flows from April to July and an increase in mean monthly flows from August through March (Muth et al. 2000). In general, changes to the natural flow have been the greatest in reach 1, and less apparent further downstream. Tributaries with natural flow regimes, such as the Yampa, act as restorers of the Green's natural flow regime.

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

Table 1. Percent change in Mean Flow at Greendale, Jensen and Green River gages due to Regulation**.** (from Muth et al. 2000)

DAM OPERATIONS 1992 TO PRESENT

Beginning in the 1980's, extensive studies were conducted to assess the environmental impacts of Flaming Gorge Dam operations and investigate the decline of native fishes in the Green River watershed. These studies resulted in the 1992 Biological Opinion on Operation of Flaming Gorge Dam, which concluded that historic dam operations jeopardized the continued existence of humpback chub, Colorado pikeminnow, and razorback sucker (USFWS 1992). The purpose of incorporating the Biological Opinion recommendations was to restore the Green River's natural hydrology. The hope was that more natural temperatures and flow patterns would create and protect critical spawning and nursery habitats for endangered fishes (Muth et al. 2000). The Biological Opinion called for full power-plant capacity releases of roughly 4800 cfs each spring and target base flows of 1100 to 1800 cfs for the remainder of the year (Muth et al. 2000).

The natural flow regime in reach 1 (Flaming Gorge Dam to the Yampa Confluence) originally had average peak flows of 11,600 cfs at the Greendale gage. Since peak releases rarely exceeded 4800cfs, Biological Opinion operations have not restored the natural flow regime in reach 1. However, the larger flows released during early summer have helped restore the natural flow regime further downstream at the Jensen gage.

Figure 9 compares the daily mean streamflow at the Jensen gage from 1994-2004 to a pre-dam hydrograph from 1948-1958. It is important to note that these two hydrographs should not be exactly identical, yet they should have similar timing and magnitudes of peak flow. The magnitude of peak flows is ultimately related to the climate and weather patterns, which are extremely variable in the Green River watershed. From 1947 to 1962, the mean annual peak at the Jensen gage was 24,000 cfs. Since 1963, the mean annual peak flow was reduced to 17,400 cfs (Muth et al. 2000). From 1992 to 2004, the mean annual peak flow was 16,350 cfs, despite operating Flaming Gorge Dam to mimic the peak floods. However, the reduction of peak flows during the last decade is more likely due to climatic conditions. Further comparison of the Biological Opinion hydrograph to the 1948-1958 hydrograph reveals that base flows have been similar since 2000. From 1992 to 2000, base flows were still elevated as a result of dam operations, despite the Biological Opinion flow recommendations.

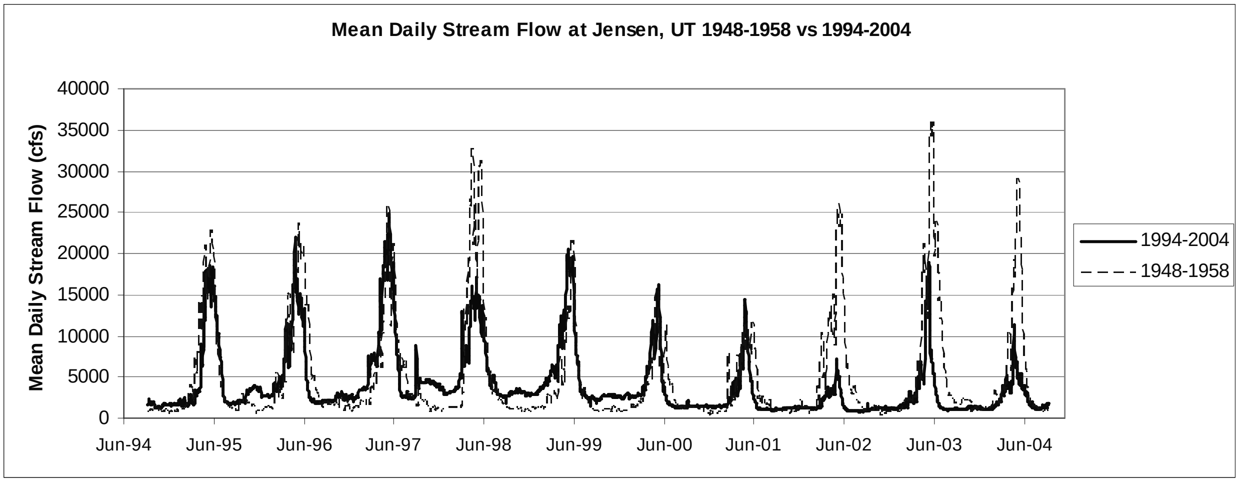


Figure 9. Comparison of a Natural Hydrograph (1948-1958) to Biological Opinion Hydrograph (1994-2004) (USGS, 2006)

The Biological Opinion flow and temperature recommendations were based on the best available scientific information. However, additional research was needed to better define river flow and temperature regimes that would benefit the endangered fishes. Further studies resulted in the 2000 Flow and Temperature recommendations, establishing particular seasonal flow rates to be achieved at different gauging stations from Flaming Gorge Dam to the Colorado confluence (Flaming Gorge Final EIS 2005). The 2000 Flow and Temperature recommendations specify spring peak releases from Flaming Gorge Dam to be 4600 cfs to greater than 8600 cfs, while the 1992 Biological Opinion specified peak releases between 4000 and 4700 cfs. Releases from Flaming Gorge Dam are to be coincident with the peak and immediate post peak flows in the Yampa. For reach 2, the Yampa confluence to the White River confluence, spring peaks are to range from 8,300 cfs to 26,500 cfs, depending on hydrologic conditions. Biological Opinion flow recommendations for the same reach ranged from 13,000 cfs to 18,000 cfs (Muth et al. 2000). In general, the 2000 Flow and Temperature recommendations allow more variability in the flow regime. Since the natural flow regime had tremendous year-to-year variability, the new recommendations will facilitate more natural peak flow magnitudes.

The Bureau of Reclamation approved the 2000 Flow and Temperature recommendations, which will be in effect during spring 2006. The overall goal of operations since 1992 has been to restore the natural flow regime, while still continuing all authorized purposes of the Colorado River Storage Project (Muth et al. 2000). A comparison of the natural hydrograph and current hydrograph at the Jensen gage reveals that recent restoration efforts have resulted in a more natural flow regime.

SERIAL DISCONTINUITY CONCEPT & GREEN RIVER HYDROLOGY

The serial discontinuity concept (SDC) is a concept that explains how rivers have an innate tendency to restore natural conditions in the downstream direction from dams because of tributary inputs. In regards to the Green River's hydrology, Table 1 of this document illustrates this aspect of the Serial discontinuity concept. Changes to the Green's natural hydrology have been greatest close to the dam and less apparent further downstream in reaches 2 and 3.

When this concept is applied to a dammed river, a discontinuity distance is calculated. This is the distance downstream from the dam at which the regulated river restores all of its characteristics to natural conditions (Stanford and Ward 2001). The Green River's hydrologic discontinuity distance has changed as a result of different flow operations since 1962. In theory, the hydrologic discontinuity distance should have greatly decreased since 1992 because more natural flow patterns have been released from the dam. While the Green River might have a more natural hydrograph at certain gauging stations, there are many other aspects of the river that are still highly unnatural. For example, years of unnatural flows have changed the sediment distribution in the river. Furthermore, other factors such as non-native vegetation, levee construction, and invasive fish species have had severe effects on the watershed. It is important to point out that the discontinuity distances, in regards to sediment distribution and other parameters of the river system are not the same as the hydrologic discontinuity distance and are probably greater. The hope is that, with continued natural flows released from Flaming Gorge, discontinuity distance for all characteristics of the river will become smaller, resulting in better habitat and increased populations of the endangered fishes.

REFERENCES

Bureau of Reclamation. Final EIS on Operation of Flaming Gorge Dam. 2005.

Grant, G.E., Schmidt, J.C., Lewis, S.L. 2003. A Geological Framework for Interpreting Downstream Effects of Dams on Rivers. American Geophysical Union 10/1029/007WS13

Muth, R. T., Crist, L.W., LaGory, Kirk E., Hayse, John, Bestgen, K.R., Ryan, T.P., Lyons, J. K. and Valdez, Richard A. 2000. Flow and Temperature Recommendations for Endangered Fishes in the Green River Downstream of Flaming Gorge Dam. A. N. L. Environmental Assessment Division,

USFWS. 1992. Final Biological Opinion on operation of Flaming Gorge Dam. Fish and Wildlife Service, Mountain-Prairie Region, Denver, Colorado.

United States Geological Survey (USGS). 2006. National Water Information System (NWIS). http://waterdata.usgs.gov

Schmidt, J. C. 1994. Compilation of historic hydrologic and geomorphic data for the upper Colorado River basin. Annual Report of Utah State University Department of Geography and Earth Resources to Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. (Recovery Program Project 37)

Stanford, J. A. and Ward, J. V. 2001. Revisiting the serial discontinuity concept. Regulated Rivers-Research & Management 17(4-5): 303-310.