The Hydrologic Regime of the Snake River in Grand Teton National Park

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Abstract

The hydrologic regime of the modern Snake River is substantially different from the estimated natural flow regime and from the regulated flow regime that existed prior to 1957, based on analysis of the record of stream flow near Moran, immediately downstream from Jackson Lake Dam, and comparison with the unregulated flow regime, as estimated by the Bureau of Reclamation. Today's late spring floods are much lower and late summer flows are much higher than if the dam did not exist. Today's fall and winter flows are approximately what they would be if there were no dam, and they are much higher than prior to 1957 when base flows were very low. Today's flood regime is much lower than those prior to 1957 but occur in a more "natural" season. Analyses were based on three techniques: traditional comparison of mean daily and instantaneous stream flow, continuous wavelet analysis, and analysis using the Indicators of Hydrologic Alteration software. The utilization of mean daily discharge data and the Bureau of Reclamation's estimated unregulated stream flow represent new contributions to the study of stream flow alteration in Grand Teton National Park.

Introduction

Jackson Lake Dam has controlled releases from Jackson Lake reservoir since 1906, thereby regulating stream flow of the Snake River through Grand Teton National Park (Fig. 1). There is a wide range of possible downstream geomorphic and ecological responses to dams that depend on the magnitude of alteration to stream flow and sediment delivery to the downstream regulated river. The purpose of this report is to describe the magnitude and characteristics of alteration of stream flow of the Snake River through the national park. This report is in partial fulfillment of work activities described in Cooperative Agreement CA-1200-99-007 between the National Park Service and Utah State University. This report is preliminary in nature and was requested as a supplemental report after negotiation of the original time frame for deliverables under this cooperative agreement.

Background: The Effects of Dams on Rivers

Dams alter the flux of water and the flux of sediment in the channel downstream from these facilities (Fig. 2). Since channel form is determined by these fluxes, alteration of the magnitude and duration of flood flows or the delivery of sediment to the channel has the potential to cause channel change downstream. The primary determinant of channel change is the relative change in the sediment transport capacity of the stream flow and the amount of sediment available for transport. Regulated stream channels can be distinguished as either in sediment deficit, sediment surplus, or equilibrium. In the former case, erosion ensues and in the middle case, channel in-filling occurs. In the latter case, no change occurs. Thus, anticipation of the geomorphic effects of dams is dependent on evaluation of the sediment budget of an impacted reach so as to determine its surplus or deficit condition.

Decisions about reversing undesired channel conditions downstream from dams are necessarily founded on natural science, engineering, and public policy. The engineering and policy considerations involve determining the costs of rehabilitation or restoration strategies and determining the likely downstream physical and ecological changes and associated public benefits of these changes. The natural science considerations are determination of the pre-human disturbance environmental condition that must stand as the standard against which rehabilitation efforts are measured, determination of the trajectory of environmental change of the riverine ecosystem that has occurred since dam construction, identification of the key linkages between environmental drivers and response variables, and determination of the ability to reverse undesired conditions. In this context, a necessary prerequisite for planning changes in dam operations is determining the magnitude of changes in stream flow, because it is one of the key environmental drivers of any river ecosystem.

Previous Analyses of Snake River Hydrology

Marston (1993) evaluated monthly hydrologic data and estimated changes in hydrology by calculating residual mass curves and synthetic hydrographs, based on changes in storage in Jackson Lake reservoir. Mott (1998) summarized these findings, as well as those of Nolan and Miller (1995).

Present Operations of Jackson Lake Dam

Releases from Jackson Lake Dam are controlled by rules adopted by the Bureau of Reclamation (USBR) within the context of the Minidoka Project and the Snake River Compact. The Minidoka Project is a complex system of interdependent reservoirs in Idaho and Wyoming whose releases serve a variety of purposes and water rights. The project was approved by Congress in 1902 and Minidoka Dam was built on the Snake River in Idaho in 1904. The Snake River Compact is the basis for the division of waters between Idaho and Wyoming and was negotiated in 1949 and ratified in 1950.

Jackson Lake Dam was the first major storage reservoir constructed on the upper Snake River and it now has an active capacity of 847,000 acre-feet. A log crib dam was built at the outlet of natural Jackson Lake in 1906, and this structure failed in 1910. The following year, the dam was reconstructed with a concrete spillway and adjoining earth-fill embankments (Mott, 1998). A larger structure was completed in 1917, which raised the natural lake level by 11.9 m (39 ft) to a full pool elevation of 6,769 feet above mean sea level.

The criteria for operating Jackson Lake and Palisades reservoirs during the spring runoff season are described in Flood Control Storage Reservation Diagram No. SN-902-1/1 and require that the discharge of the Snake River in normal runoff years be controlled to 20,000 ft^3/s or less as measured at U. S. Geological Survey (USGS) gaging station 13037500, Snake River near Heise, Idaho. This gage is located upstream from the confluence of the Snake River with the Henry's Fork. This operating rule also establishes that 75 percent of the reservoir flood control space be located in Palisades Reservoir and 25 percent in Jackson Lake reservoir. Decisions about dam releases from Jackson Lake and Palisades during the flood runoff season are made on a daily basis, based on daily inflow and seasonal runoff projections.

The present decision process for determining releases from Jackson Lake in the remainder of the year are described by the Bureau of Reclamation and State of Wyoming (1996) and are briefly summarized below. This decision process incorporates compact requirements, legal water rights, and the interests of a wide range of water users, only one of which is the National Park Service.

Fall and winter releases from Jackson Lake are set at the greater of either 280 ft^3/s or the computed inflow to the lake if the lake elevation is higher than 6760.95 ft AMSL. If the reservoir elevation is less, then dam releases are to be the lesser of 280 ft^3/s or the computed inflow to the reservoir. Dam releases may differ from these rules under some storage conditions in Jackson Lake. The governing criteria regarding dam releases during the onset of spring snowmelt are based on the available flood control space in Jackson Lake, the projected likelihood of filling the reservoir at the end of the spring runoff season, and snow pack and melting conditions. Releases subsequent to the spring snowmelt inflow balance many competing objectives that include reservoir boating, white-water rafting, scenic floating in the national park, fishing interests, and special requests of the Wyoming Game and Fish Department. These interests are given an opportunity to express their desires at a public meeting held in Jackson in mid-May of each year.

The typical operating scenario is that Jackson Lake is maintained near its full capacity as long as possible so as to prolong the reservoir boating season. As natural flood runoff subsides, dam releases are increased so as to facilitate white-water and scenic boating downstream and to move water from Jackson Lake to Palisades Reservoir. Reclamation tries to establish a flow that can be sustained through September 30, which is now considered the end of the recreational boating season. The total volume of water that must be moved downstream in a normal year is 200,000 acre-feet. This value is adjusted in years of above or below average runoff.

Study Area

Most of the inflow to Jackson Lake is derived from National Park Service lands, and most of the remainder is from Forest Service lands. The drainage area of the Snake River within or upstream from Yellowstone National Park is 485 mi^2, which is 60 percent of the total drainage basin area upstream from Jackson Lake Dam. Most of the remaining watershed is within the John D. Rockefeller Memorial Parkway or Grand Teton National Park.

Pacific Creek and Buffalo Fork drain the Absaroka Mountains and are major tributaries that enter the Snake River downstream from the dam. Stream flow of the Snake River was gaged at the south boundary of Yellowstone National Park between 1913 and 1925 (station number 13010000) and has been gaged above Jackson Lake at Flagg Ranch, Wyoming (station number 13010065), near Moran, Wyoming (station number 1301100) since 1903, and at Moose, Wyoming (station number 13013650) since 1995. Pacific Creek has been gaged since 1917, and Buffalo Fork was gaged near Moran (station number 13011900) between 1917 and 1960 and has been gaged above Lava Creek near Moran (station number 13012000) since 1965.

Methods

Previous studies of the characteristics of stream flow of the Snake River did not analyze changes in mean daily discharge nor utilize available estimates of mean daily discharge in the absence of Jackson Lake reservoir. Thus, the techniques and the data base used in this report represent new contributions.

Historical streamflow change and variability

The hydrologic characteristics of the Snake River near Moran during the last century were analyzed using mean daily discharge data measured by the USGS at its gages and synthetic natural stream-flow data representative of unregulated conditions as computed by the USBR. Thus, there are few measurements of unregulated flow because gaging only began 3 years before construction of the initial lag crib dam at Jackson Lake, but the USBR data base provides a unique benchmark against which to compare actual measurements with estimated unregulated stream flow.

The estimated mean daily unregulated stream flow data are available from the USBR Pacific Northwest Region Hydromet data archives (http://www.usbr.gov/pn/hydromet/webhydarcread.html). These data estimate what stream-flow conditions would have been in the absence of flow regulation. Average daily natural stream flow was computed as the daily change in reservoir storage plus the observed daily discharge, likely involved use of the Army Corps of Engineers river routing computer model, but did not account for evaporation or reservoir seepage loss (Jim Doty, USBR-Pacific Northwest Division, personal communication)..

The daily flow and annual peak discharge data were divided into three analysis periods: 1903-1916, representing years before a permanent Jackson Lake Dam was built, 1917-1956, years following the construction of a permanent dam and establishment of the present maximum full pool elevation, and 1957-2002, following the construction of Palisades Reservoir. We calculated the Log Pearson III recurrence interval of various magnitude flood events of the measured and estimated unregulated flow records.

The measured mean daily discharge data for the Snake River near Moran were used to calculate median, 25th percentile, and 75th percentile stream-flow values for each day of the three time periods. These data were compared to the median daily stream-flow values calculated with the estimated unregulated discharge data.

We also examined the timing of peak discharge based on measured and estimated unregulated discharge data. We compared the timing of peak discharge on the main-stem Snake River to that of Pacific Creek and Buffalo Fork and gages on the Snake River at Flagg Ranch (USGS gage 13010065) and at Moose.

Wavelet analysis of the measured stream-flow record of the Snake River near Moran

Continuous wavelet transformation is a powerful analytical tool with which to analyze the hydrologic effects of dams. Spectral analysis, of which wavelet analysis is an emerging technique, provides a new method with which to evaluate cyclic attributes of stream-flow at all time scales without the necessity of pre-assigning time frames. This technique is based on signal frequency variation that is highly visual, mathematically based, and statistically testable. Wavelet analysis (Kumar and Foufoula-Georgiou, 1997; Mallat, 1999) is similar to Fourier analysis but instead of sine and cosine functions, employs one of a series of different wavelet functions, each composed of a scaling and detail wavelet. We conducted a continuous wavelet transformation (CWT) on the Snake River data, in which the wavelet is translated throughout the input signal, often a vector containing time series data, such as the continuous mean daily discharge record analyzed here. We used the CWT as described by Torrence and Compo (1998), in which the reader will find a comprehensive review of the theory and methods of wavelet analysis.

Indicators of Hydrologic Alteration

An Indicators of Hydrologic Alteration (IHA) analysis was performed on the mean daily discharge data for the Snake River near Moran, using both the actual measured values and the estimated unregulated stream flow. The IHA software was used to compute 33 ecologically-relevant hydrologic parameters for five different statistics groups: the magnitude of monthly water conditions, the magnitude and duration of annual extreme water conditions, the timing of annual extreme water conditions, the frequency and duration of high and low pulses, and the rate and frequency of water condition changes (Richter et al. 1996). The IHA output consists of non-parametric statistics that compare "pre-impact" versus "post-impact" hydrologic data.

Results

Historical stream-flow change and variability

The flood regime of the Snake River near Moran did not change greatly between 1904 and 1956, despite construction of Jackson Lake Dam. The magnitude of the 2-year flood decreased by 4 percent and the 10-year flood increased by 4 percent from the pre-permanent dam period (1904-1916) to the post-permanent dam period (1917-1956) (Fig. 3). In contrast, the magnitude of the 2-year flood decreased 31 percent and the 10-year flood decreased by 26 percent between the pre-Palisades period (1917-1956) and post-Palisades period (1957-2002).

Comparison of the magnitude of the estimated 2- and 10-year floods in the absence of flow regulation with measured flood regime also indicates that the natural flood regime has been more greatly disrupted since 1957. The actual 2-year and 10-year floods for the 1917-1956 period are 4 and 6 percent, respectively, less than the estimated flood regime in the absence of flow regulation for the same period. In contrast, the actual 2-year and 10-year floods for the 1957-2002 period are 42 and 36 percent, respectively, less than the estimated flood regime in the absence of flow regulation for that period. In fact, the estimated flood regime of the Snake River after 1957 is greater than for the period prior to 1956, in contrast to the large reduction in floods that have actually occurred.

The greatest changes to the annual flow regime also occurred after 1957, based on comparison of the median hydrographs of the three time periods. The natural hydrology of the Snake River was altered as soon as the first dam was constructed at Jackson Lake in 1906, based on comparison of median hydrographs of the estimated natural regime to the actual stream flow for the period prior to completion of the permanent dam in 1916 (Fig. 5). The greatest divergence between the estimated unregulated stream flow and the actual discharge was the decreased stream flow during rise of the annual snowmelt flood in May and increased stream flow between mid-July and mid-September. In some years, the actual discharge was nearly zero between Mid-October and mid-December. After completion of Jackson Lake Dam in 1917, the annual flood was artificially delayed about 2 months, although the magnitude of this flood was about the same as the estimated unregulated flood would have been, and the rate of rise and recession of this flood was approximately the same (Fig. 6). In contrast, the estimated unregulated stream flow for this period was characterized by the slower recession than rise of the annual flood, as is typical of most unregulated streams. Median stream flow was nearly zero between October 1and April 1. Since 1957, the magnitude of the annual flood has been greatly decreased, although the time of the annual peak is now nearly the same as would have been the estimated unregulated flood (Fig. 7). Stream flow has been nearly steady between about July 1 and September 15, and subsequent base flows are approximately what they would have been if the dam did not exist.

The overall hydrology of the upper Snake River basin is illustrated by hydrographs for 1996 in which the snowmelt flood from Yellowstone Park, as measured at Flagg Ranch, peaked on about June 1 (Fig. 8). The estimated unregulated flood would have peaked near Moran about 1 week later and dam releases delayed the peak another 7 to 10 days. The magnitude of the flood at Flagg Ranch was about 15 percent larger than that of the downstream gage near Moran. The resulting hydrograph at Moose is due to the combined influence of the delayed flood release from the dam and later-timed inflows from Pacific Creek and Buffalo Fork, as well as artificially high base flows between mid-July and October 1.

Another perspective concerning alterations to the timing of stream flow is provided by comparing the date and magnitude of each year's annual peak flood for a number of gages in the upper Snake River basin (Fig. 9). This comparisons further illustrates the delayed timing and reduced magnitude of floods that have occurred since completion of Jackson Lake Dam, because the post-dam floods typically occur outside the range of all estimated unregulated floods.

Wavelet analysis of the measured stream-flow record of the Snake River near Moran

Image colors in a CWT plot are an exponential representation of the wavelet power with dark brown being the highest power and blue the lowest power. Colors do not correspond to a hydrologically meaningful value and are simply a visual indication of relative wavelet power. The solid black U-shaped line on each plot is the cone of influence, below which edge effects limit confidence in interpretation of results. Statistically significant results are inside the labeled 95 percent confidence interval. The x-axis shows time, at a daily resolution. The logarithmic y-axis shows the wavelet scale.

The primary conclusion to be drawn from the CWT analysis is further support for the finding that there was a change in dam operations in 1957, and that the modern Snake River of the past few decades has had weaker cyclic fluctuations than did the river prior to 1957. The most significant wavelet scale is that of the one-year cycle, indicated in red (Fig. 10). The constancy of the red pattern centered on 1 year, prior to 1957, is an indication of the reliability of this hydrologic feature prior to completion of Palisades Dam. Afterwards, the strength of this signal weakens and was non-existent in the late 1950s and late 1980s, years of drought. Prior to 1957, there was also a weak cycle with a frequency of about 180 days that reflects the annual repeatability of the sequence of sustained very low flows between October 1 and April 1 and flood flows in June, July, and August. The strength of the 6-month cycle was greatest between about 1918 and 1928 and has not been a characteristic of the Snake River since completion of Palisades Dam.

Indicators of Hydrologic Alteration

The IHA analyses further confirm the magnitude of hydrologic change that has occurred in Snake River subsequent to completion of Palisades Dam. Many of the IHA parameters are similar to those discussed in previous sections, and they indicate how altered is the Snake River's hydrology (Table 1).

Magnitude of Monthly Water Conditions:

The present hydrologic regime involves significant reduction of the monthly mean discharge in April, May, and June and significant increases in monthly mean discharge in July, August, and September, based on comparison of estimated unregulated stream flow and actual measurements. These deviations are not as great, however, as the deviations between estimated and actual stream flow for the period between 1917 and 1956.

Magnitude and Duration of Annual Extreme Water Conditions:

The primary characteristic of today's Snake River is the elevated base flows and decreased flood flows; in contrast, the Snake River had much lower base flows and a more normal flood regime in the period between 1917 and 1956. The 1-day and 3-day minimum flows of the Snake River are now much higher than they would be in the absence of Jackson Lake Dam, but the 30-day and 90-day minimum flows are now lower. In all cases, metrics of maximum flow, from the 1-day maximum to the 90-day maximum, are all lower than they would be in the absence of the dam. These characteristics are very different from the attributes of the Snake River in the period between 1917 and 1956 when the actual minimum stream flow for all durations measured in the IHA analysis were lower than estimated for unregulated flow. In contrast, there was less difference between the magnitudes of high flows for various durations.

Timing of Annual Extreme Water Conditions:

The delayed date of the peak flood is evident in the IHA analysis, as it is in the other results discussed above.

Rate/Frequency of Water Condition Changes:

Today's Snake River changes stage, and discharge, much more slowly than would the river under unregulated conditions, because the rise and fall rates for actual flows are much less than for estimated unregulated flow. In contrast, the rise and fall rates for actual flows were much greater than from estimated stream flows for the 1917 to 1956 period.

Discussion and Conclusions

The availability of estimated unregulated stream flow data provides a unique opportunity to compare the present flow regime of the Snake River to what might exist in the absence of the dam and its present operating regime. Although the establishment of minimum base flows have returned the river to a natural flow regime for the 6 month period between about October 1 and April 1, the flow regime of the other half of the year is profoundly altered. The basis for these alterations is the decision to control floods and to maintain artificially high discharges for recreational boating. Thus, the 2-year recurrence flood is now about 5,800 ft^3/s, whereas it would be about 9,900 ft^3/s if uncontrolled. Median mean daily discharge in late summer is now about 2,500 ft^3/s, whereas it would be about 500 ft^3/s if uncontrolled. The regulated flow regime has also changed greatly since completion of Palisades Dam in 1957. Prior to that time, base flows were much lower, and magnitude of floods was more nearly that of the uncontrolled hydrology, and the timing of floods was delayed about 2 months. These changes in hydrology are consistent with the geomorphic studies of Mills (1991), who found increased sedimentation at the mouths of tributaries that enter the Snake River downstream from the dam and increased horizontal stability elsewhere. The next stage in the present research effort is to reevaluate changes in sediment transport and geomorphic response of the Snake River during the twentieth century.

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