Effects of Jackson Lake Dam on the Snake River and its floodplain, Grand Teton National Park, Wyoming, USA

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Abstract

In 1906, the Bureau of Reclamation created Jackson Lake Dam on the Snake River in what later became Grand Teton National Park. The geomorphic, hydrologic and vegetation adjustments downstream of the dam have yet to be documented. After a larger reservoir was completed further downstream in 1957, the reservoir release schedule from Jackson Lake Dam was changed in a manner that lowered the magnitude and frequency of floods. The stability of the Snake River exhibited a complex response to the change in flow regime. Close to major tributaries, the Snake River increased in total sinuosity and rates of lateral channel migration. Away from the influence of tributaries, the river experienced fewer avulsions and a decrease in sinuosity. Vegetation maps were constructed from 1945 and 1989 aerial photography and field surveys. Using these data, we determined how vegetation is directly related to the number of years since each portion of the floodplain was last occupied by the channel. The vegetation has changed from a flood-pulse dominated mosaic to a more terrestrial-like pattern of succession. Changes in the Snake River and its floodplain have direct implications on bald eagle habitat, moose habitat, fish habitat, safety of rafting and canoeing, and biodiversity at the community and species levels.

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1. Introduction

Rivers are dynamic features of the landscape whose characteristics vary over time and space with changes in environmental controls. The outlet of
Jackson Lake was dammed in 1906. This log-crib dam washed out in 1910 and was replaced by a larger structure in 1918 that raised the lake level by 11.9 m (39 ft) (Fig. 1). The reservoir thus created has since been operated to provide irrigation water to areas in Idaho during the summer, although the importance of this function changed after closing of Palisades Dam in 1957. Repairs on Jackson Lake Dam, completed in 1989 at a cost of $76 million, have not affected the lake level or changed the schedule of reservoir releases on the Snake River. The purpose of this project is to document the effects of Jackson Lake Dam on flows and stability of the Snake River, and the subsequent impact of these changes on floodplain vegetation and related resources. The physical integrity of rivers downstream from dams has been given increased attention, as science-driven policy seeks to balance the beneficial aspects of dams with ecosystem concepts such as landscape complexity and improved access to salmonid habitat (Malanson, 1993; Graf, 2001; Downs and Gregory, 2004; Pohl, 2004; Wohl, 2004).

The Snake River has been classified as premier trout waters of national importance because of habitat quality (Ostresh et al., 1990). Recreational boating, including scenic float trips and guide services for fishing cutthroat trout, generates US$25–30 million annually to the local economy. The river is used for wintering and resting/rearing habitat for trumpeter swans, shorebirds and ducks. Streamside trees, especially dead snags, are used by bald eagles and osprey for summer and nesting habitat. The Snake River floodplain is used as a migration corridor and for summer habitat for elk, mule deer, antelope and bison. The floodplain is also used as a migration corridor and winter habitat for moose.

2. Background

Only a few published scientific studies involving the Snake River in Grand Teton National Park were found. Mekeel (1972) provided a cursory description of flows and sediment regimes in the river and its major tributaries. Kroger (1973) reported the effect of fluctuating water levels on the aquatic ecology of the river. Love and Antweiller (1974) examined river sediment in the area. Kiefling (1978) summarized the channel characteristics that affect the Snake River cutthroat trout. These studies were largely reconnaissance in nature and did not address geomorphic changes in this section of the Snake River or vegetation communities along the floodplain. Marcus et al. (2002) described and explained the spatial distributions of large woody debris in the same section of the Snake River discussed in this paper.

Knighton (1987) and Graf (1988) described the channel characteristics expected in the downstream

![Fig. 1. Jackson Lake Dam, after reconstruction was completed in 1988.](image-url)
direction of stream channels as well as aberrations introduced by merging tributaries. In the absence of tributaries, these trends include decreasing slope and particle size and increasing channel depth and sinuosity. Changes in gradient and channel pattern are manifestations of adjustments to main-stem incompetence to flush sediments introduced by tributaries.

Natural and artificial dams upset streamflow regime by trapping sediment and impeding the flow of water. Petts (1979) summarized the extensive literature on the geomorphic effects of reservoirs and pointed out that following adjustments can be expected following river impoundment: decreases in peak flows, bedload discharge, width and bankfull cross-sectional area; increases or decreases in depth, gradient and sinuosity. Williams and Wolman (1984) found that stream beds degraded immediately below the 21 dams that they studied primarily during the first 20 years following dam closure. In contrast to Petts, they found channel width did not necessarily decrease. Bradley and Smith (1986) found narrower channels, degraded channels and a reduced rate of channel migration below the Fresno Dam on the Milk River, Montana.

Quantitative relationships between the dynamics of stream channels and landscape diversity on floodplains could provide a basis for changing flow releases from dams to maintain or achieve desired channel patterns and vegetation mosaics. Williams and Wolman (1984) found that riparian vegetation cover increased downstream from dams by as much as 95%, a condition they believe “probably” results from the reduction in magnitude, frequency and duration of destructive floods. They concluded that increased low flows are not necessarily the reason for increased vegetation. Turner and Karpiscak’s (1980) comparative-photographs study of the Colorado River below Glen Canyon Dam found that increased riparian vegetation narrowed the channel in many reaches. Bradley and Smith (1986) found that reduced flooding led to significantly reduced cottonwood populations on the floodplain below the Fresno Dam.

Akashi (1988) found large-scale reductions in channel length and sinuosity in a section of the Bighorn River following the closing of the new Boysen Dam in north-central Wyoming. In addition, this study area was marked by increasing shrublands and decreasing woodlands. Nanson and Beach (1977) discuss the interrelationship between geomorphology and forest succession on a meandering-river floodplain. They found a strong interrelationship between overbank sedimentation and vegetation “within the total floodplain system”. Harris (1988) confirmed significant associations between six geomorphic valley types and the unique composition of riparian vegetation communities. The vegetation-geomorphic units can be differentiated into landscape elements, each sensitive to different management practices. Hupp (1990) associated stream valley geomorphology (e.g., fluvial landforms, channel geometry, streamflow characteristics, channel gradient and stream order) and certain riparian vegetation patterns. Flow duration and flood frequency were found to be the most important factors in maintaining vegetation pattern. Swanson (1980), in his review article, also inferred a strong interdependence between geomorphic processes and vegetation communities. “Live and dead vegetation regulates rates of geomorphic processes, which, in turn, destroy vegetation, create new opportunities for establishment and influence the development of plant communities” (Swanson, 1980, p. 168). In a later paper, Swanson et al. (1988) point to the significant influence that landforms have on geomorphic and biotic patterns and processes. They suggest that such influence is so complex as to preclude identification of specific effects of landforms on the ecosystem. Zimmermann and Thom (1982) determined that at the scale of landforms (e.g., slopes, floodplains, ridges, terraces, etc.) physical processes determine the mosaic of vegetation patterns, with the latter only secondarily involved in a feedback role.

Baker (1989) studied variation in riparian vegetation at the regional scale and found that macro-scale (e.g., elevation and drainage basin morphology) and micro-scale (e.g.: channel width) variables are linked with neither having pervasive control. In a companion paper, Baker (1990) concluded that regional pattern in richness of riparian vegetation cannot be explained with any single variable.

Kalliola and Puhakka (1988) show that flood magnitude and duration are probably the most important factors controlling the vegetation mosaic through the combined mechanisms of erosion and sedimentation. This finding was echoed in a study of the regeneration of bald cypress (Shankman and
where the creation of oxbow lakes through disturbance by channel migration was found to be vital to species maintenance. Flood disturbance rather than a repeating successional process controls the riparian vegetation structure on rivers that are inherently unstable (Baker, 1988). Hanson et al. (1990) developed a computer model that includes the dispersibility of tree species in simulating riparian forest fragmentation at the landscape scale.

Salo et al. (1986) studied the upper Amazon River and proposed that the high diversity of the lowland forest is created and maintained by the lateral erosion and deposition of the meandering river. Bravard et al. (1986) determined that the diversity of the vegetation community is determined by the fluvial dynamics along a section of the Upper Rhone River. Amoros et al. (1987) studied the same section of the Upper Rhone in four dimensions (i.e., upstream–downstream, cross-valley, epigeal-ground water and time), holistically combining geomorphic pattern, fluvial dynamics and vegetation processes.

3. Study area

The Snake River drainage above Moose, Wyoming covers approximately 4500 km² (1740 miles²), most of which is situated within Grand Teton and Yellowstone national parks (Figs. 2 and 3). A 42.0 km (26.1 miles) long section of the Snake River and its

Fig. 2. The Snake River study area, Wyoming, Middle Rocky Mountains, USA.
floodplain was studied between Jackson Lake Dam and Moose, Wyoming, in Grand Teton National Park. The 100-year floodplain of the Snake River between the dam and Moose covers an area of 31.9 km² (7883 acres). Major tributaries entering the Snake River along this section are Pacific Creek, Buffalo Fork and Spread Creek. These tributaries and the main river itself flow through outwash resulting from the Pine-dale glaciation. Three bedrock units dominate the geology of the upper Snake River drainage: Quaternary rhyolite flows, Paleozoic/early Mesozoic sedimentary rocks (limestone, sandstone, red shale and siltstone interbedded with sandstone) and Tertiary volcanics (rhyolite flows, welded tuffs, breccias, andesite flows and basalt flows). Widespread slope failures in these geologic units add significant

Fig. 3. Color aerial photograph of the study section. Jackson Lake Dam is located at the outlet of the lake near the top of the photo. Compare to Fig. 2 for scale.
volumes of coarse sediment to tributaries of the Snake River. Jackson Lake Dam is situated on porous volcanic rock and unconsolidated lacustrine, glacial and alluvial sediments.

Multiple glaciations have occurred in Jackson Hole (Love et al., 2003). The Bull Lake glaciation ended about 35,000 years BP and left till and outwash in Jackson Hole. These deposits are overlain by loess that has been dated by C-14 dating of fossil shells at 13,000 to 19,000 years BP. The Pinedale glaciation reached its maximum extent in Jackson Hole about 9000 years BP and was less extensive than previous glaciations. The uppermost deposits in Jackson Hole are outwash from Pinedale age glaciations. Meltwater from the retreating Pinedale ice cut through the outwash to create a series of terraces, probably between 9000 and 6000 years BP.

Precipitation in the Snake River drainage generally increases with elevation and ranges from 500 to 1000 mm (20–40 in.) in Jackson Hole to over 1500 mm (60 in.) on the high peaks of the Tetons (Despain, 1987; Ostresh et al., 1990). Seasonal runoff is strongly controlled by the timing of snowmelt. Runoff in unregulated streams rises in April–May, reaches a peak in June–July and recedes in August–September. Low flows occur from October–March (Marston and Anderson, 1991).

Vegetation on the floodplain of the Snake River is dominated by blue spruce (*Picea pungens*), narrowleaf cottonwood (*Populus angustifolia*) and mountain alder (*Alnus incana*). Russet buffaloberry (*Shepherdia canadensis*), willow (*Salix spp.*), bearberry honeysuckle (*Lonicera involucrata*) and Utah honeysuckle (*L. utahensis*) are the major shrubs (Shaw, 1976).

### 4. Methods

#### 4.1. Effects of the dam on flows and channel stability

**4.1.1. Residual mass curves and hydrograph analyses**

The first step in examining the stability of the Snake River channel was to analyze time series data on flows released from Jackson Lake Dam. Data were available on water discharge of the Snake River near Moran from 1903 to 1989 and end-of-month reservoir storage data for Jackson Lake from 1912 to 1979. Residual mass curves and synthetic hydrographs could then be compiled as part of these analyses. A residual mass curve reveals time intervals during which flow was greater than the mean (portions of the curve with a positive slope) and time intervals during which flow was less than the mean (portions of the curve with a negative slope). Therefore, it can reveal when major shifts may have occurred in the water release schedule from Jackson Lake Dam. Synthetic hydrographs reveal what the flow in the river would have been had the dam not been in place. In months when Jackson Lake was gaining storage, this increase can be added to the flow of the Snake River near Moran to determine what the flow would have been had the dam not been in place. Conversely, in months when Jackson Lake was losing storage, this loss can be subtracted from the flow of the Snake River below the dam to determine what the flow would have been had the dam not been in place.

**4.1.2. Field surveys of channel morphology**

The second step in understanding geographic patterns of channel stability was to conduct field-based surveys during the summer of 1989 to collect data on geomorphic characteristics of the stream channel. Data were collected by visual estimation techniques in 372 transects along the 42.0 km (26.1 miles) study section on the following parameters:

1. channel unit type: pools (slow, deep water with little or no surface agitation), glides (fast, deep water with little or no surface agitation), riffles (fast, shallow water with surface agitation but no standing waves), rapids (fast, deep water with considerable surface agitation, including standing waves);
2. bankfull depth: calculated by adding direct measurements of water depth and depth from the water surface to bankfull stage; and
3. streambed particle sizes: bedrock, large boulders (>900 mm), small boulders (300–900 mm), large cobbles (150–300 mm), small cobbles (75–150 mm), coarse gravel (25–75 mm), fine gravel (2.5–25 mm), sand–silt–clay (<2.5 mm).

These data were organized in the DBASE III Plus database program. Scatterplots of each variable against transect distance below the dam were generated using the SPSS/PC+ V3.0 statistical program.
The scatterplots were used together with plan-view channel maps to delineate distinct reaches along the study area. The location of major tributaries and large erosional cutbanks was also annotated on the scatterplots so that the influence on channel morphology could be discerned.

4.1.3. GIS analyses of lateral channel shifting

The third step in understanding the geographic pattern of channel stability was to map plan-view channel changes through time. A computer search to find aerial photographs and topographic maps was conducted through the Aerial Photography Field Office of the Agricultural Stabilization and Conservation Service in Salt Lake City during 1990. Manual searches were also conducted at the offices of Grand Teton National Park, Yellowstone National Park, University of Wyoming-National Park Service Research Center, University of Wyoming Remote Sensing Center in the Department of Geology and Geophysics, and the Geological Survey of Wyoming. The following maps and photos were collected:

1. 1899 topographic map (scale=1:125,000) published by the U.S. Geological Survey;
2. 1921 base map (scale=1:125,000; poor channel definition) published by the U.S. Forest Service;
3. 1945 black-and-white aerial photos (scale=1:40,000; excellent quality) from the National Archives;
4. 1968 topographic map (scale=1:24,000) published by the U.S. Geological Survey;
5. 1975 black-and-white orthophotos (scale=1:24,000) published by the U.S. Geological Survey;
6. 1983 National Wetlands Inventory map (scale=1:24,000) published by the U.S. Fish and Wildlife Service;
7. 1989 color infrared aerial photos (scale=1:40,000, excellent quality) from the USDA-ASCS, Aerial Photography Field Office.

Maps and photos were georectified and converted to a common scale of 1:24,000. The 1899 map, although drafted to USGS cartographic standards, must be considered less detailed at a scale of 1:125,000 than the other river maps. The width of the pre-dam river, as depicted on this map, probably represents a wide braided belt that prevailed at the time rather than a constant single-thread bankfull channel. Detail within the braided channel is missing at this scale. Nevertheless, this map was included in the overlay process because it does accurately document the portion of the floodplain that was occupied by the channel. From these maps and the photos, plan-view maps of the Snake River from Jackson Lake Dam to Moose were produced and show the channel pattern that existed for each of the years 1899, 1921, 1945, 1967, 1968, 1975, 1983 and 1989. Criteria defined by Cowardin et al. (1979) for the U.S. Fish and Wildlife Service National Wetlands Inventory were followed in mapping the channel. Using the nomenclature of Cowardin et al., the “permanently flooded habitat” was shown on the plan-view maps in a solid tone and the “intermittently exposed” and “semi-permanently flooded” habitats were shown with a stippled pattern.

Total sinuosity was measured from the plan-view maps following the Richards’ (1982) guidelines. Total sinuosity is computed by dividing the total channel length (including all active meandering, braided and compound channels) by the straight-line distance between inflection points through the channel belt. Graf (1988) defines compound channels as a transitional pattern between meanders and braids. At low flows, a compound pattern consists of a single meandering channel; at high flows, a braided pattern is observed, but with one subchannel clearly dominant over the others.

The 100-year floodplain was transferred from 1989 Federal Emergency Management Agency maps to our plan-view maps. The width of the floodplain was then measured at regular intervals along the study section. Channel gradient was calculated from 1:24,000 scale U.S. Geological Survey topographic maps.

The seven channel maps between 1899 and 1989 were digitized using the vector-based ArcInfo geographic information software. These vector-based files were then rasterized and imported into IDRISI, a raster-based geographic analysis software package. Each individual raster cell has a length and width of 80.5 m (264 ft), the average width of the active Snake River channel or 0.65 ha (1.6 acres) in area. The entire 100-year floodplain between Jackson Lake Dam and
Moose required 4927 cells to cover the area of 31.9 km² (7883 acres). All seven rasterized channel maps were then overlaid in IDRISI to create a composite map that showed the time since a given cell was last occupied by the active channel. Sections of the floodplain, where the channel has not been stable, will show an abundance of cells with low frequencies of channel occupancy. The probabilities of channel change have been analyzed with geographic information systems by Graf (1981, 1984) and by Wasklewicz et al. (2004).

4.2. Changes in vegetation on the floodplain

4.2.1. Field surveys of vegetation

Field surveys of vegetation were carried out during the summer of 1990 at 60 sites in the 100-year floodplain between Jackson Lake Dam and Moose. Sites were selected primarily to provide equal representation of the five tentative vegetation mapping units: grass covered, shrub-swamp, narrowleaf cottonwood, mixed narrowleaf cottonwood and blue spruce, and blue-spruce dominated. Black and white aerial photographs taken in 1945, along with 1975 orthophoto maps, were used in producing the initially proposed vegetation communities. An attempt was made to survey an equal number of sites occupied by the five vegetation communities in each of the five study area reaches. Accessibility of a proposed site, however, was necessarily taken into account in final selection of a site.

Two 100-m transects were laid out parallel to the stream channel at each site. Using the point-centered quarter method (Mueller-Dombois and Ellenberg, 1974), tree data (for all plants at least 2 m tall)
were collected at 10-m intervals for species (Shaw, 1976), distance-from-center-point, breast-height diameter or circumference and tree height. Ground cover, detritus, soil type and shrub (between 0.3 and 2 m tall) species were recorded in accordance with the line-intercept method (Mueller-Dombois and Ellenberg, 1974).

The field data were entered into a spreadsheet program that calculated tree density, dominance and frequency values along with weighted averages of cover/shrubs variables. In addition, descriptive statistics and correlation coefficients were computed in SPSS/PC+. Cluster analysis was performed also in SPSS/PC+ to categorize the field data into landscape mapping units. Basal area (density x average basal area) of blue spruce (P. pungens), narrowleaf cottonwood (P. angustifolia) and lodgepole pine (Pinus contorta) were the variables clustered in defining the tree communities. The variables clustered for the non-forest communities (vegetation taller than 1 ft and shorter than 2 m) were the percent cover of groundcover (e.g., grasses and forbs), sand, detritus, willow (Salix spp.), bare ground (no live vegetation), shrubby cinquefoil (Potentilla fruticosa), narrowleaf cottonwood (P. angustifolia), silverberry (Elaeagnus commutata), russet buffaloberry (S. canadensis), mountain alder (A. incana) and big sagebrush (Artemisia tridentata). The number of landscape mapping units utilized was a function of the results of the cluster analysis and the ability to resolve those units on the 1:40,000 scale of the aerial photographs from which the communities were to be mapped.

4.2.2. Mapping vegetation on the floodplain and measuring landscape biodiversity

Photokeys of vegetation were developed for 1945 (black and white panchromatic) and 1989 (color infrared) aerial photographs, the earliest and latest years such photos of the study area were available. Because of the small scale of the photographs (scale=1:40,000), pattern, contiguity, texture and, in

![Fig. 5. Actual hydrographs (bold lines) and virgin flow (i.e., if Jackson Lake Dam was not in-place) for the Snake River near Moran for periods before and after Palisades Reservoir was completed in 1957.](image-url)
the case of the 1989 photos, color were the
discernable characteristics included in the photokeys
(Avery and Berlin, 1985; Lillesand and Kiefer, 1987).
Using the photokeys and a zoom transferscope,
boundaries of the vegetation communities were then
added to the 1945 and 1989 plan view channel maps.
The vegetation maps were published as plates 3 and 7
vegetation maps were then digitized using the same
procedure described earlier for digitizing the seven
channel maps. By overlaying the two vegetation maps
and the channel maps, it was possible to construct
matrices of vegetation change: one for the portion of
the floodplain disturbed by the channel and one for
the portion of the floodplain not disturbed by the
channel.

Following the recommendation of Turner (1989),
Romme’s (1982) relative evenness formula was used
in this study as the appropriate index of landscape
diversity:

\[ H = - \ln \sum p_i^2 \]  

(1)

Where \( p_i \) = proportion of landscape covered by \( i \)
community type. The maximum value for relative
evenness for a landscape containing six mapping units
is 1.788.

5. Results

5.1. Effects of the dam on flows and channel stability

5.1.1. Residual mass curves and hydrograph analyses

The change in reservoir release schedule for
Jackson Lake Dam can be detected by examining
the residual mass curve of summer-period (June–
August) mean daily flow for the Snake River near
Moran (Fig. 4). The effect of the regional drought in
the 1930s is apparent on summer releases. Even
more important, construction of Palisades Reservoir
downstream led to a dramatic decrease in summer
peak flows as Jackson Lake was no longer the
primary irrigation water storage facility. Synthetic
hydrographs of the Snake River near Moran have
been constructed using the residual mass curves as a
guide, to show the influence of dam operations on
streamflow and channel change (Fig. 5). The differ-
ence between the virgin flow (i.e., flow without the
Fig. 6. Flow frequency curves for the Snake River near Moran before and after Palisades Reservoir was completed in 1957.
and the actual flow in the Snake River for the period 1912–1956 is a matter of timing rather than magnitude. Jackson Dam did not have a major affect on channel forming flows during this period. The difference between the virgin flow and actual flow during the period 1957–1979, however, shows a dramatic decrease in summer peak flows caused by the dam. Virgin flows in the two periods are quite similar and indicate that climate has not had a significant affect on channel changes. Finally, the frequency and magnitude of actual peak flows decreased after Palisades Reservoir went into operation (Fig. 6). Gaging station data show that the Snake River below Jackson Lake Dam experienced peak flows greater than 275 m$^3$/s [9712 cubic feet per second (cfs)] during 13 years between 1899 and 1945 but only one flow of that magnitude between 1945 and 1955. From 1955 through 1968, no peak flow exceeded 229 m$^3$/s (8070 cfs) and from 1968 through 1975 no peak flow exceeded 198 m$^3$/s (7000 cfs). In 1981, a 323 m$^3$/s (11,400 cfs) peak flow was recorded. All of the evidence points to a decline in the competence of the Snake River for sediment transport and an accordant loss of destructive flows for vegetation occurred after 1957.

5.1.2. Field surveys of channel morphology

Distinct spatial trends in several morphological variables were evident along the Snake River. The 42.0 km (26.1 miles) study section was divided into five reaches on the basis of stream habitat type, bankfull water depth, size distribution of streambed particles, channel gradient, floodplain width and total sinuosity (Table 1). Reach 1 extends from the dam to Pacific Creek, a distance of 6.97 km (4.33 miles) in a low-gradient single channel dominated by pools and sand and finer-sized streambed particles. Reach 2 extends 6.53 km (4.06 miles) from Pacific Creek to Sagebrush Island with pronounced braiding among mid-channel bars and a streambed dominated by coarse gravel and small cobbles. Reach 3 extends 10.41 km (6.47 miles) from Sagebrush Island to

<table>
<thead>
<tr>
<th>Reach</th>
<th>Reach 2</th>
<th>Reach 3</th>
<th>Reach 4</th>
<th>Reach 5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel morphology (units as shown)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance downstream from Jackson Lake Dam (km)</td>
<td>0.00 to 6.97</td>
<td>6.97 to 13.50</td>
<td>13.50 to 23.91</td>
<td>23.91 to 30.09</td>
<td>30.09 to 42.00</td>
</tr>
<tr>
<td>Reach length (km)</td>
<td>6.97</td>
<td>6.53</td>
<td>10.41</td>
<td>6.18</td>
<td>11.91</td>
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<tr>
<td>Flood plain width (m)</td>
<td>292</td>
<td>860</td>
<td>1227</td>
<td>518</td>
<td>1044</td>
</tr>
<tr>
<td>Net reach relief (m)</td>
<td>6.10</td>
<td>12.19</td>
<td>18.29</td>
<td>15.24</td>
<td>39.62</td>
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<tr>
<td>Slope (m/km)</td>
<td>0.88</td>
<td>1.87</td>
<td>1.75</td>
<td>2.47</td>
<td>3.33</td>
</tr>
<tr>
<td>Water depth (m)</td>
<td>0.73</td>
<td>0.82</td>
<td>1.01</td>
<td>0.85</td>
<td>0.88</td>
</tr>
<tr>
<td>Bankfull depth (m)</td>
<td>3.17</td>
<td>2.13</td>
<td>2.16</td>
<td>1.98</td>
<td>2.01</td>
</tr>
</tbody>
</table>

| Substrate composition (percentage) | | | | | |
| Bedrock | 0 | 0 | 0 | 0 | 0 |
| Large boulders (>900 mm) | 2 | 0 | 0 | 3 | 0 |
| Small boulders (300 mm–900 mm) | 3 | 0 | 0 | 4 | 2 |
| Large cobbles (150 mm–300 mm) | 5 | 6 | 18 | 34 | 30 |
| Small cobbles (75 mm–150 mm) | 13 | 30 | 41 | 35 | 34 |
| Coarse gravel (25 mm–75 mm) | 18 | 39 | 23 | 19 | 21 |
| Fine gravel (2.5 mm–25 mm) | 13 | 17 | 15 | 4 | 11 |
| Sand/clay (<2.5 mm) | 46 | 8 | 3 | 3 | 10 |
| Total | 100 | 100 | 100 | 100 | 100 |

| Channel unit type (percentage) | | | | | |
| Pools | 58 | 7 | 4 | 0 | 0 |
| Glides | 35 | 82 | 68 | 69 | 63 |
| Riffles | 11 | 28 | 19 | 35 | 23 |
| Rapids | 0 | 0 | 0 | 12 | 2 |
| Total | 100 | 100 | 100 | 100 | 100 |
Deadman’s Bar in a single channel with a substrate dominated by small cobbles. Reach 4 extends 6.18 km (3.84 miles) from Deadman’s Bar to Frustration Ponds and is comprised of a predominantly braided pattern. Reach 5 extends 11.91 km (7.40 miles) from Frustration Ponds to Moose in a steep-gradient, compound channel.

5.1.3. GIS analyses of lateral channel shifting

Channel maps for the 7 years between 1899 and 1989 were originally published as Plates 1–7 in the thesis by Mills (1991). An example of the channel migration and changes in channel pattern for one section of the Snake River is illustrated in Fig. 7. The total sinuosity index (Table 2 and Fig. 8), derived from

Fig. 7. An example of channel changes for the same section of the Snake River.
these maps, revealed greater values and greater fluctuation in Reaches 2, 3 and 5, than those with wider floodplains (Reaches 1 and 4). Reach 1 was found to be the most stable of the five reaches in that it exhibited the lowest temporal variation in total sinuosity. That reach was comprised of the highest percentage of pools (58%), highest bankfull depth (3.17 m), highest percentage of sand/clay (46%) in the substrate, lowest gradient (0.88 m/km) and the narrowest floodplain (292 m).

Greater channel instability was apparent in the lower four reaches. Pacific Creek, Buffalo Fork and Spread Creek have added coarse sediment to the main channel along Reach 2. Large and steep cutbanks, responsible for aggradation and braiding, were found in Reach 2 and Reach 5. Particle size increased downstream along the study section, another indication that the river had insufficient competence to transport its sediment load in its lower reaches. Wider floodplains in the Reaches 2, 3 and 5 allow opportunities for greater channel migration.

In this study, the total sinuosity index is used as an analog for channel stability. The values (and range) of total sinuosity were found to be lowest in the reaches with the narrowest floodplains (Reaches 1 and 4). Even though dam operators released lower peak flows and higher low flows after Palisades Reservoir was closed in 1957, the hypothesized decrease in the values (and range) of total sinuosity was not witnessed. The explanation for this anomaly is presented below.

Total sinuosity increased from 1899 to 1945 in response to the 13 annual peak flows that exceeded 275 m$^3$/s (9712 cfs) during that period. Peak flows tend to open new channels and cause an overall increase in braiding. With only one annual peak flow exceeding 275 m$^3$/s (9712 cfs) between 1945 and 1955, total sinuosity decreased as overflow channels were abandoned and braids were converted to

<table>
<thead>
<tr>
<th>Year</th>
<th>Reach 1</th>
<th>Reach 2</th>
<th>Reach 3</th>
<th>Reach 4</th>
<th>Reach 5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1899</td>
<td>1.20</td>
<td>1.44</td>
<td>1.42</td>
<td>1.35</td>
<td>1.50</td>
<td>1.39</td>
</tr>
<tr>
<td>1921</td>
<td>1.13</td>
<td>1.31</td>
<td>1.40</td>
<td>1.21</td>
<td>1.37</td>
<td>1.29</td>
</tr>
<tr>
<td>1945</td>
<td>1.50</td>
<td>2.05</td>
<td>1.91</td>
<td>1.23</td>
<td>1.81</td>
<td>1.73</td>
</tr>
<tr>
<td>1968</td>
<td>1.46</td>
<td>2.23</td>
<td>2.68</td>
<td>1.61</td>
<td>2.69</td>
<td>2.18</td>
</tr>
<tr>
<td>1975</td>
<td>1.43</td>
<td>1.74</td>
<td>1.78</td>
<td>1.35</td>
<td>1.80</td>
<td>1.47</td>
</tr>
<tr>
<td>1983</td>
<td>1.50</td>
<td>2.65</td>
<td>2.73</td>
<td>1.45</td>
<td>2.14</td>
<td>2.12</td>
</tr>
<tr>
<td>1989</td>
<td>1.45</td>
<td>2.33</td>
<td>2.00</td>
<td>1.43</td>
<td>3.09</td>
<td>2.21</td>
</tr>
<tr>
<td>Range</td>
<td>0.37</td>
<td>1.34</td>
<td>1.33</td>
<td>0.40</td>
<td>1.91</td>
<td>0.92</td>
</tr>
<tr>
<td>Mean</td>
<td>1.38</td>
<td>1.96</td>
<td>1.99</td>
<td>1.38</td>
<td>1.97</td>
<td>1.77</td>
</tr>
</tbody>
</table>

Fig. 8. Total sinuosity index for the five reaches of the Snake River between Jackson Lake Dam and Moose, Wyoming.
compound channels. During this period, sediment contributions from Snake River tributaries was negligible. From 1955 to 1968, when annual peak flows were consistently less than 220 m$^3$/s (8070 cfs), Pacific Creek added significant volumes of sediment to the main channel. Total sinuosity increased as a response to new deposits of coarse sediment in the Snake River that accumulated in expanded point bars and new mid-channel bars. From 1968 to 1975, annual peak flows were less than 198 m$^3$/s (7000 cfs) and total sinuosity dropped once again. The 323 m$^3$/s (11,400 cfs) peak flow in 1981 opened old channel braids. The total sinuosity increased from 1975 to 1983 in response to this event.

The channel composite maps illustrate an important geographic pattern of stability. Immediately downstream of major sediment sources, such as Pacific Creek and high erosional cutbanks, the Snake River is characterized by lower horizontal stability (i.e., an abundance of cells with low frequencies of occupancy) because the Snake River no longer has sufficient flows to flush the sediment additions. Away from the influence of tributaries and cutbanks, the Snake River is characterized by higher horizontal stability (i.e., an abundance of cells with high

Fig. 9. Time since last channel occupance for 0.65 ha (1.6 acre cells in the 100-year floodplain of the Snake River between Jackson Lake Dam and Moose, Wyoming).
frequencies of occupance) because channel avulsions are not as frequent (Fig. 9).

5.2. Changes in floodplain vegetation

5.2.1. Field surveys of vegetation

Cluster analysis results were combined with visual inspection of 1945 and 1989 aerial photographs (Tables 3 and 4, Fig. 10) to identify the six distinct landscape units (five vegetation communities and one unvegetated mapping unit) that exist in the study area:

1. Unvegetated channel deposits (U)
2. Grass covered deposits (G)
3. Shrub-swampland of willow–mountain alder (S)
4. Low-density narrowleaf cottonwood (C)
5. Medium-density mixed blue spruce–narrowleaf cottonwood (M)
6. High-density blue spruce (S)

5.2.2. Mapping vegetation on the floodplain and measuring landscape biodiversity

The trend in landscape mapping units is toward greater evenness in four of the five reaches, indicating a tendency toward older serial stages of vegetation. Fig. 11 shows the proportion of the study area occupied by the different vegetation communities. Inspection of that figure reveals a trend toward the climax blue spruce community type (all three forest communities increased) and an increase in the grass-covered and bare-ground landscape units. Relative evenness, $H$ in Eq. (1), increased from 1.505 in 1945 to 1.637 in 1989. The increase in blue spruce is a response to the decline in destructive floods, allowing vegetation succession to proceed. The increase in unvegetated and grass-covered landscape units reflects the effect of declining competence of the Snake River to transport sediment loads introduced from Pacific Creek, Buffalo Fork, Spread Creek and erosional cutbanks along the study section.

The rasterized maps of time since last channel occupance were overlaid with the 1989 vegetation map to assess if a relationship could be discerned. A chi-square analysis was performed on these data to see if the null hypothesis could be rejected that no statistically significant difference in vegetation exists between cells of different intervals since last channel occupance (Table 5). The null hypothesis was rejected at the $p < 0.001$ level, indicating a strong control on the progression of vegetation succession by the past channel migration history on the floodplain.

Another null hypothesis was proposed that no statistically significant difference exists between floodplain mapping units in terms of resistance to horizontal channel migration. Again, a chi-square test was utilized (Table 6). The null hypothesis was rejected at the $p < 0.001$ level, indicating a strong control on channel migration by vegetation.

The results of these two chi-square tests reveal that once blue spruce vegetation gets established on the floodplain, its relatively high resistance to destruction will allow it to expand at the expense of other communities. A positive feedback exists, so blue spruce should thrive in stable reaches of the river but struggle to gain a foothold in unstable portions.

### Table 3

<table>
<thead>
<tr>
<th>Mapping unit</th>
<th>Pattern/contiguity</th>
<th>Texture</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989 color infrared photos</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unvegetated</td>
<td>Continuous, open</td>
<td>Smooth</td>
<td>White</td>
</tr>
<tr>
<td>Grass-covered</td>
<td>Strips, open</td>
<td>Mottled</td>
<td>Light green</td>
</tr>
<tr>
<td>Shrub-swamp</td>
<td>Continuous, open</td>
<td>Stippled</td>
<td>Red/green</td>
</tr>
<tr>
<td>Cottonwood</td>
<td>Strips, loose</td>
<td>Coarse</td>
<td>Green/red</td>
</tr>
<tr>
<td>Mixed forest</td>
<td>Clumps, dense</td>
<td>Coarse</td>
<td>Green/red</td>
</tr>
<tr>
<td>Blue spruce</td>
<td>Continuous, very dense</td>
<td>Coarse</td>
<td>Dark green</td>
</tr>
</tbody>
</table>

### Table 4

<table>
<thead>
<tr>
<th>Vegetation communities</th>
<th>Years since last channel occupance</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>Unvegetated</td>
<td>94</td>
<td>62</td>
</tr>
<tr>
<td>Grass-covered</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>Shrub-swamp</td>
<td>34</td>
<td>26</td>
</tr>
<tr>
<td>Cottonwood</td>
<td>36</td>
<td>25</td>
</tr>
<tr>
<td>Mixed forest</td>
<td>10</td>
<td>17</td>
</tr>
<tr>
<td>Blue spruce</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>203</td>
<td>147</td>
</tr>
</tbody>
</table>

Calculated $X^2 = 246.8$, critical $X^2 = 52.62$ ($df = 25$, $p = 0.001$).
Predictions of vegetation change were accomplished by applying the same rates of change for 1945–1989 (Table 7) to the 1989 data. Table 7 reveals the total number of cells in each landscape unit in 1945 (e.g., 676 in water, 1717 in shrub-swamp) and the total number of cells in each landscape unit in 1989 (e.g., 665 in water, 721 in shrub-swamp). The numbers in the matrix indicate the percentage change of each landscape unit from 1945 to 1989. For instance, 50.9% of the 1945 channel was also in water in 1989;
30.5% of the cottonwood had changed to a mixed forest by 1989. The assumption must be made that Jackson Lake Dam will be operated in the 44 years after 1989 in the same manner that it had been operated in the previous 44 years. The predictions indicate that low-density cottonwood and moderate-density mixed stands of cottonwood-blue spruce will become the most dominant landscape units by 2033 (Table 7). The shrub-swamp landscape unit, dominated by willow and alder, will continue to decline and blue spruce will continue to expand. The other landscape units show relatively little change. The relative evenness (landscape diversity) of floodplain mapping units will continue to increase, although at a

![Mosaic of Floodplain Vegetation](image)

**Table 5**

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Observed area (ha) destroyed</th>
<th>Expected area (ha) destroyed</th>
<th>Relative susceptibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unvegetated</td>
<td>69.6</td>
<td>33.2</td>
<td>2.10</td>
</tr>
<tr>
<td>Grass</td>
<td>88.4</td>
<td>72.2</td>
<td>1.22</td>
</tr>
<tr>
<td>Shrub-swamp</td>
<td>97.5</td>
<td>145.4</td>
<td>0.67</td>
</tr>
<tr>
<td>Cottonwood</td>
<td>67.6</td>
<td>65.7</td>
<td>1.03</td>
</tr>
<tr>
<td>Mixed forest</td>
<td>35.1</td>
<td>39.7</td>
<td>0.88</td>
</tr>
<tr>
<td>Blue spruce</td>
<td>1.3</td>
<td>3.3</td>
<td>0.39</td>
</tr>
<tr>
<td>Total</td>
<td>359.5</td>
<td>359.5</td>
<td>1</td>
</tr>
</tbody>
</table>

*E* = expected frequency is calculated by taking the percent of each vegetation type in the entire floodplain, excluding water, and multiplying this percent by the total observed number of disturbed cells (=553).

*b* Susceptibility = O/E; using chi-square test, calculated $\chi^2 = 93.7$, critical $\chi^2 = 20.5$ (df = 5, $p = 0.001$) differences are significant at $p = 0.001$.

**Table 6**

<table>
<thead>
<tr>
<th>1945 communities # cells</th>
<th>1989 communities # cells</th>
<th># cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water 50.9 18.2 6.7 7.0 12.7 3.8 0.7 676</td>
<td>Unvegetated 12.1 56.7 5.3 6.3 13.6 6.0 0 397</td>
<td></td>
</tr>
<tr>
<td>Grass-covered 9.1 11.4 14.3 12.1 31.6 20.1 1.4 854</td>
<td>Shrub-swamp 5.6 2.2 12.3 22.1 38.4 17.5 1.9 1717</td>
<td></td>
</tr>
<tr>
<td>Cottonwood 8.5 3.7 8.9 12.3 32.6 30.5 3.5 778</td>
<td>Mixed forest 6.6 3.0 6.6 13.5 9.8 43.4 17.1 468</td>
<td></td>
</tr>
<tr>
<td>Blue spruce 5.4 0 29.7 18.9 27.0 18.9 0 37</td>
<td>Mixed forest 6.6 3.0 6.6 13.5 9.8 43.4 17.1 468</td>
<td></td>
</tr>
<tr>
<td>Total # cells 665 525 511 721 1380 969 156 4927</td>
<td>Blue spruce 5.4 0 29.7 18.9 27.0 18.9 0 37</td>
<td></td>
</tr>
</tbody>
</table>
slower rate of change, from 1.505 in 1945 to 1.637 in 1989 and to 1.667 in 2033.

6. Conclusions

Changes in the release schedule for Jackson Lake Dam in 1957 have led to a reduction in the frequency and magnitude of peak flows that trigger channel change and destroy floodplain vegetation. The Snake River is less stable immediately downstream from tributaries and erosional cutbanks because of the decline in stream competence. The river is more stable some distance downstream from the sediment sources because of the decline in channel avulsions. Overall, this latter response is most dominant over the length of the study section.

Channel stability greatly influences the dynamics of vegetation on the floodplain of the Snake River. Unstable reaches of the river experienced an increase in landscape diversity (as measured by relative evenness) between 1945 and 1989. Stable reaches experienced a decrease in diversity. Overall, diversity increased from 1945 to 1989, a trend that is predicted to continue to 2033 if Jackson Lake Dam continues to be operated as it has since 1945. These trends are intimately tied to the time since last channel occupancy and the relative resistance of vegetation to channel migration.

The geomorphic changes in the Snake River and related changes in floodplain vegetation create beneficial and adverse impacts on other river and riparian resources in Grand Teton National Park. Reservoir operations since 1957 have increased landscape diversity on the floodplain, a recognized goal of global resource management. Biodiversity at the species level along the Snake River, however, has decreased by the expansion of species-poor forested vegetation communities at the expense of species-rich willow-alder shrub-swampland. The increase in blue spruce provides more potential nesting and rearing sites for bald eagles and osprey. The decline of the willow-alder shrub-swampland results in a net loss of winter food for moose. The decline in channel avulsions has eliminated numerous side-channels that formerly served as spawning and rearing habitat for the Snake River cutthroat trout. On the other hand, the possibility that rafting and canoeing enthusiasts might choose the wrong channel has declined as fewer choices are available with the lower braiding. Resource management officials of the National Park Service wish to work in concert with the Bureau of Reclamation, who operates Jackson Lake Dam, to design a reservoir release schedules that maximizes the resource values discussed above.

Acknowledgements

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References