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GEOMORPHIC CONTROLS ON HYDRAULIC PROCESSES OF BLACKTAIL DEER CREEK, YELLOWSTONE NATIONAL PARK

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INTRODUCTION

The Greater Yellowstone Ecosystem spans 22 million acres of national park, national forest, national wildlife refuge, and BLM land in Wyoming, Montana, and Idaho ("What is the Greater Yellowstone Ecosystem?," n.d.). The GYE is home to the largest concentration of wildlife in the 48 contiguous states (Chan et al., 2016). With the protected Yellowstone National Park at its heart, it is a key location for ecosystem research. Trophic cascade theory is an ecologic model explored here. It predicts that altering one ecosystem element can result in system-wide change; even seemingly unrelated ecosystem factors are closely connected through a chain of cause and effect relationships (Herendeen, 1995).

In Greater Yellowstone, some research has employed trophic cascade theory to understand how changes in the wolf population have initiated widespread ecological effects including potential impacts to the physical habitat of streams. The eradication of wolves in the early 20th century led to increased elk populations and their resultant browsing of riparian vegetation (Kay, 1997; Ripple and Beschta, 2003). With reduced aspen and willow branches to construct dams, beavers moved to larger streams and crafted bank burrows. Beaver dams that may have historically pooled water to form shallow, wide, regularly inundated floodplains (Gurnell, 1998; Polvi and Wohl, 2011; Persico and Meyer, 2012; Giriat, 2016) fell into disrepair and eventually broke up during high discharge flood events (Butler and Malanson, 2005). As dams and ponds were eradicated, stream slope increased causing incision into the previous floodplain (Wolf et. al., 2007; Ripple and Beschta, 2017). The

resulting deep, wide channels prevented overbank flooding and instead developed small inset floodplains flanking river flow within the steep, newly formed channel banks (Beschta and Ripple, 2006, 2019).

In order to better characterize channel geometries and their controls, this study investigated what surfaces flood at various discharges. Since predicting bank-full discharges often requires more nuanced study than field observations (Knighton, 1998), detailed cross section topography surveys were collected to create hydraulic models of inundation depths and lateral extent along five stream reaches. We explored if surfaces on the valley floor are inundated during high frequency flood events. We also compared flooding along different stream sections and considered other possible controls (stream migration, bank collapse, alluvial fans, and stream discharge) on valley floor inundation. Ultimately, we modeled floodplain inundation as a means to understand Blacktail Deer Creek's complex historic morphology and explored the role that beaver dam removal (and trophic cascade theory by extension) may have played.

STUDY AREA

Blacktail Deer Creek consists of two prominent tributaries, the west and east forks, which join south of Grand Loop Road. On the Blacktail Deer plateau the stream network is superimposed on kame terraces and outwash channels from the Pinedale glaciation (22-15 ka (Licciardi and Pierce, 2018). Current stream flow is confined within the bottom of these outwash channels for river reaches 4EF, 3EF, and 2EF (Fig. 1). Along this region, the east fork meanders through valley fill deposits alternating from deep pools to



Figure 1. Overview of river reaches with cross sections.

riffle sequences. Both east and west tributaries exit restrictive outwash channels to meander across a gently sloping alluvial fan overlaying kame terrace deposits (reaches 1EF and WF). 1EF alternates between muddy pools along meander bends and shallow riffle sections lined by small willows. The west fork is faster flowing with cobbles, gentle meanders, larger willows, and wider steep channels.

METHODS

To characterize the floodplain inundation of Blacktail Deer Creek, we simulated stream geometry and discharge by integrating RTK GPS measurements and LiDAR DEM imagery. Historic stream gage data and calculated flood recurrence intervals provided representative stream discharges that were used to develop inundation maps.

Field Data Collection

GPS-surveyed stream cross sections along the east and west forks of Blacktail Deer Creek complemented DEM datasets by providing elevation data among willows and beneath water flow. Along the west fork, we gathered cross sections extending upstream from the east fork confluence. On the east fork, we collected cross section coordinates along four reaches (1EF, 2EF, 3EF, and 4EF) representative of changing geomorphic surroundings (Fig. 1).

Real-time kinematic (RTK) GPS connections, where a hand-held GPS rover referenced a base station with precise satellite coordinates, provided GPS coordinates with 13 cm accuracy in dense foliage. We spaced cross sections at approximately 20-meter intervals, selecting locations accessible between willows and representative of general flow (meander bends, straight sections, and alternating riffle and pool segments). Data points included locations of elevation change along the banks, water surface, channel edge, channel elevation changes, and thalweg. Water levels represented low August discharges.

Estimating Peak Discharges

Discharge values were derived from both measured and modeled data. Historic stream gage data from the U.S. Geological Survey provided peak discharges from 1937-1941 for the east fork (2020a) and 1937-1946 and 1988-1993 for the west fork (2020b). A regression model calibrated for northwestern Wyoming streams calculated representative flows for various flood recurrence intervals (Miller, 2003):

$$Q_{\rm T} = K(A^a) \left(\left(\frac{E - 3,000}{1,000} \right)^e \right) ((L - 100)^l)$$

where Q_T is discharge at a recurrence interval of T years (cubic feet per meter), K is a regression constant, A is watershed area (square miles), E is average basin elevation (feet), L is longitude (decimal degrees), and a, e, and l are regression coefficients (Table 1). We generated GIS polygons of the east and west fork watersheds to calculate basin areas of 9 square miles and 15 square miles, respectively. The GIS zonal statistics tool linked the watershed areas to the DEM raster to calculate mean basin elevations of 727.6 m for the west fork and 714.5 m for the east fork. The average longitude was 110.589675°. We utilized 2 and 10-year floods to characterize high recurrence interval flood discharges.

Hydraulic Modeling of Flood Discharges

LiDAR DEM data gathered using the point tool in ArcMap complemented field GPS cross-sectional data, which provided accurate coordinates where the LiDAR DEM could not penetrate foliage and water. GPS and DEM points were then integrated as single Excel files for each of the four river reaches.

The Hydrologic Engineering Center's River Analysis System (HEC-RAS) was used to generate stream flow and inundation models from this cross-sectional data. We measured distance in meters between cross-

Flood Recurrence Interval (year)	West Fork Q m^3/s	East Fork Q m ³ /s	
1.5	2.4	1.4	
2	3.0	1.8	
5	5.0	3.1	
10	6.4	4.0	
25	8.3	5.3	
50	9.6	6.3	
100	11.1	7.3	
500	14.9	10.0	

Table 1. Calculation of flood peak discharges

sections for the left bank, channel, and right bank with the RAS ruler. Manning's n roughness values for the floodplains and channel (Table 2), which estimated the frictional impact of vegetation and rocks upon water flow, were selected according to the guidelines outlined by Chow (1959) and Arcement and Schneider (1989). Bank edges were estimated as data points closest to the waterline of a 2-year flood modeled by steady flow analysis. Levies were inserted to prevent simulated flows from inundating paleochannels and other low elevation regions before first overtopping channel banks. Steady flow analysis simulated flow as an unchanging discharge along the stream utilizing our regression values and available gage data. Manning's equation approximated characteristic upstream and downstream flow through the normal depth option in HEC-RAS. To calculate this value, we estimated the friction slope (Brunner and Gee, n.d.) as the change in mid-channel elevations over the change in total horizontal displacement for each cross-section reach (Table 2). The critical depth model was calculated as a mixed regime flow (Goodell, 2011) to account for changes between stable subcritical flow along gentle slopes and turbulent supercritical flow corresponding with steeper slopes (Ponce, n.d.).

Various discharge values on RAS-Mapper were then simulated to visually depict the extent of floodplain inundation. After drawing the river path to specify which flow paths the river should follow between cross-sections, we generated a new background terrain map combining the detailed LiDAR-DEM with

Table 2. Values used for HEC-RAS hydrologic modeling

	WF	1EF	2EF	3EF
Floodplain Manning's n (unitless)	0.12	0.1		
Channel Manning's n (unitless)	0.05	0.06		
Reach Slope (unitless)	0.02	0.023	0.008	0.024



Figure 2. Cross sections with a 0.7 m2/s flood displaying (a) characteristic alluvial cross section (1EF 6) with a well-defined lower floodplain and upper surface, (b) cross section 2EF 5 displaying a stepped slip-off terrace on the left bank and a steep kame terrace on the right bank characteristic of reaches 4EF, 3EF, and 2EF, and (c) light gray DEM line captures a willow in the middle of the actual channel of cross section 4EF 1. Legend names represent the following: EG PF 1 is the energy gradeline peak flow, WS PF 1 is the water surface peak flow, Crit PF 1 is the critical peak flow, Ground is the ground elevation, Levee is the bank levee, Bank Sta is the cross section number, and Current Terrain is the LiDAR DEM elevation.

our interpolated cross-sectional stream geometry to eliminate willow elevations (Fig. 2c). The resulting maps depict the extent of inundation for 2-, 10-, and 100-year floods along the west fork, and <1.5- (i.e., the maximum recorded discharge of 0.7 m³/s), 10- and 100-year floods for the east fork.

RESULTS

Stream Discharge Values

The limited historic stream gage data and calculated regression discharge values provided an estimate of flood recurrence intervals. Our east fork regression predictions (Table 1) averaged 37% greater than Beschta and Ripple's (2019) values. Our calculated

1.5-year discharge was 100% larger than the maximum stream gage flood ($0.7 \text{ m}^3/\text{s}$) measured in four years (1937-1941) (U. S. Geological Survey, 2020a). However, the same discharge event along the Yellowstone River at Corwin Springs was also smaller than a 1.5-year recurrence interval (U. S. Geological Survey, 2020c). Stream regressions for the west fork align at 8% higher than Beschta and Ripple's (2019) values. According to our calculations, the maximum stream gage prediction $(4.0 \text{ m}^3/\text{s})$ for 1937-1946 (U. S. Geological Survey, 2020b) was a 2- to 5-year flood, which compares closely to the Yellowstone River's corresponding 2-year flood (U. S. Geological Survey, 2020c). The maximum 5.1 m^3/s discharge (2020b) had a 5-year recurrence interval, which aligns with the same event creating a 10-year flood along the Yellowstone River (2020c). Since our regression values along the east fork we high, we incorporated the maximum east fork gage discharge of $0.7 \text{ m}^3/\text{s}$ with 2-, 10-, and 100-year discharges in the inundation maps.

Inundation Modeling

Reaches 4EF, 3EF, and 2EF inundated a similar region surrounding the channel (Fig. 3). Channel geometries for a 0.7 m³/s discharge varied from 0.38-1.1 m deep and 0.8-7.5 m wide as they altered between deep, steep channels to channels of similar depth and width. Floodplains occurred at a variety of heights ranging from 0.5 to 1.6 m above the channel base.

1EF demonstrated two characteristic reaches with floodplain inundation and channel depth decreasing and channel width increasing near the confluence (Fig. 3). The upper channel of 1EF (cross sections 20 to 15) was 0.4-0.9 m deep and 1.3-2.8 m wide at a 0.7 m³/s discharge and did not have consistent floodplain levels. Paleochannels now separated by fan/ terrace surfaces radiated from this upper extent and did not inundate. The middle section (cross sections 14-4) had channels 0.4-0.7 m deep and 1.8-3.6 m wide. A small surface 0.7-1.3 m above the channel base inundated with a 5-year flood, while the higher surface (0.9-1.2 m above the channel) inundated with a 50-year recurrence (Fig. 2a). Bank collapse was observed as a common feature along meander bends. Downstream (cross sections 3 to 0), channels were shallower (0.3-0.6 m) and wider (2.8-4.2 m) at



maximum recorded east fork flood (0.7 m³/s)
2-year flood (3.04 m³/s for WF)
10-year flood (6.40 m³/s for WF, 4.04 m³/s for EF)
100-year flood (11.1 m³/s for WF, 7.29 m³/s for EF)

Figure 3. Blacktail Deer Creek inundation at different discharges.

a 0.7 m³/s flow, and had extremely uneven channel beds from underlying kame terrace boulders. Two surfaces occurred at similar 0.8-1.2 m and 1.0-1.4 m heights above the channel bed. However, the lower surface required larger 10- to 25-yr floods to inundate, and the upper surface was not inundated even a by a 500-year flood. The inundation map (Fig. 3) similarly demonstrated that flooding is widespread between cross sections 15-5 (flood waters would have extended beyond the edge of our cross-section geometries had we not created artificial channel edges) and decreased between cross sections 3-0.

The west fork did not widely flood; 2-, 10-, and 100-year floods were generally confined within steep channel banks (Fig. 3). Channel geometry was an inconsistent 0.3-1.0 m deep and 4.0-14.4 m wide for a 2-year flood. Numerous dry or swampy paleochannels lay alongside the stream that did not activate during flooding events.

DISCUSSION

Much of our research assumes that flood recurrence intervals are predictable measures of bank-full discharge. We recognize that actual flooding can be more variable. Particularly, predictions for 1.5year bank-full channels may flood less frequently (Williams, 1978). Our data functions best as a general comparison between various stream sections with the same stream controls instead of as precise predictions of future inundations at specific locations.

Beschta and Ripple's (2019) interpretation that floodplain shape and inundation was characterized by the former presence and recent absence of beavers should impact various reaches of the river similarly. Elk populate the entire region, equally browsing foliage along both reaches of the creek. Gnawed twigs in the sedimentary record and current beaver dams indicate that beavers are active along both the east and west forks. Trophic controls remain the same between all reaches, but channel geometry and floodplain inundation vary significantly between the sections of Blacktail Deer Creek. Geologic and geomorphic controls must be considered to adequately explain for the changing river hydraulics.

Stream migration, impacted by underlying kame and valley fill deposits, may account for key floodplain characteristics of 4EF, 3EF, and 2EF. The lowest surfaces did not form as inset-floodplains following recent stream incision since these surfaces vary in height and inundate at different discharges. What Beschta and Ripple (2019) identified as the higher

historic floodplain exhibits similar variation. Instead of two clear floodplains, multiple notched levels gently slope towards the current channel and represent slipoff terraces (Fig. 2b). Trapped between unerodable kame terraces, the upper east fork laterally migrated and gradually carved multiple channels.

Unlike the three upstream east fork reaches, 1EF exhibits two inundation surfaces (Fig. 2a) that correspond to the historic and inset floodplains that Beschta and Ripple (2019) describe. Field observations indicate some of these lower surfaces originated as bank failures. As the meandering river incised fine alluvial fan sediments, cut banks collapsed into the channel to form lower inundation surfaces.1EF floods differently along various sections of the alluvial fan. Above the confluence, the east fork drops to match the elevation of the west fork resulting in headward fan erosion, increased channel slope, and reduced floodplain inundation. Large boulders indicate that the stream has incised to meet the underlying kame terrace deposit.

Floodplain inundations also significantly differ between the two river tributaries. Although the west fork is pinned between kame terraces similar to 4EF, 3EF, and 2EF, the west fork floods less land. The west fork's higher discharge effectively transports sediment downstream and incises steep banks that prevent flooding.

The variety of Blacktail Deer Creek's channel geometries indicate an old, complex floodplain history shaped by a variety of geomorphic controls. The Pinedale glaciation covered Yellowstone's Northern Range with large kame terraces (Licciardi and Pierce, 2018). Melting glaciers released large quantities of sediment that filled outwash channels with aggrading river terraces and alluvial fans from the early to late Holocene. Around 3.3 ka, glacial sediment transport decreased according to terrace charcoal dating (Persico and Meyer, 2009). Blacktail Deer Creek, constrained between kame terraces began to incise the Holocene valley fill deposits to create various slip-off terraces. The lower alluvial fan continued to slowly aggrade to the present day.

CONCLUSIONS

Previous explanations of channel characteristics that extend trophic cascade theory to stream morphology cannot adequately explain changes in channel geometry and floodplain inundation along Blacktail Deer Creek. While trophic cascade-related events may impact the physical morphology of channels, multiple additional geologic and geomorphic controls determine channel and floodplain geometries more significantly than the absence of beaver dams. Since the late Pleistocene, stream migration, alluvial deposition, bank collapse, and stream discharge have gradually shaped Blacktail Deer Creek.

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