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EVERY PEBBLE COUNTS: RECONSTRUCTING THE FLUVIAL HISTORY OF BLACKTAIL DEER CREEK IN THE NORTHERN RANGE OF YELLOWSTONE NATIONAL PARK

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INTRODUCTION

In 1872, Yellowstone National Park was established as the first ever National Park in the United States. The park has a long history of management strategies that have affected the ecosystem (Haines 1977). A particularly well-studied area of the park is the Northern Range, a ~1,530 km^2 area of relatively low elevation land that is the wintering range of Yellowstone's northern elk herd (Houston 1982, Clark et al. 1999). The impact of management in this ecosystem is subject of much debate (Yellowstone National Park 1997). Among the most controversial of these management practices is the extirpation and eventual reintroduction of wolves (canis lupus) from the ecosystem. In the early 1900s, the management of the park focused on protecting "good animals", primarily grazing ungulates that could be conserved within the park and hunted when they moved outside of the park boundaries. This brand of conservation was heavily encouraged by the hunting industry that realized without protection, there would be fewer animals to hunt (Yellowstone National Park, 1997). Due to this priority, apex predators were killed inside and outside of the park and by the mid 1920s, wolves had been completely removed from the Yellowstone Ecosystem (Chadde, Kay 1991). Following the removal of wolves, elk (cervis elaphus) populations greatly increased causing overgrazing of willow (Salix spp.), aspen (populus tremuloides) and other plant populations (Kay 1997).

Some research suggests that the removal of apex predators has affected stream processes and morphology as part of a widespread trophic cascade initiated by the removal of wolves. The decrease in willows in riparian areas has been suggested to cause destabilization of stream banks causing both channel incision and widening (Beschta, Ripple 2011). Due to this change in channel dimensions, the normal stream flows are less likely to flood the channel in a high frequency flood event, resulting in historic floodplains that are now abandoned (Ripple, Beschta 2018).

There are other factors that influence channel morphology and dynamics besides interactions between willow and streambanks. For example, the size of sediment that makes up the bed material determines channel morphology (Meyer 200) and what size floods are needed to cause channel incision. The size of sediment is an important variable in the dynamics of the stream channel. Sediment size will govern what size flood discharges are required to mobilize the bed material and therefore change the channel shape (Knighton 1998). Larger sediment size requires a greater discharge, which makes streams of this size with large diameter materials generally more stable and unmoving while streams of this size with smaller sediment can be expected to shift shape and location along the floodplain. Less research has focused on the fluvial geomorphic history of the streams and the factors that directly affect channel shape.

Our study is focused on creating a detailed characterization of the bed material of Blacktail Deer Creek by comparing the shear stress generated in various sized, historical floods to the shear stress of the bed material to understand the extent and potential for sediment transport. We aim to reconstruct a more complete understanding of the history of the stream by comparing historical images from the last 80 years.

Figure 1. Researchers in the East Fork of Blacktail Deer Creek measure the diameter of pebbles using a gravelometer. Each person would walk in a zig-zag pattern across the width of the stream until at least 100 pebbles were measured for each section.

We predict that the large clasts in the glacial sediment are too large to be transported by the modern Blacktail Deer Creek. Thus, this creates bed armor that that the stream cannot mobilize. This bed armor prevents net vertical cutting and minimal lateral movement of the channel.

Blacktail Deer Creek is located near the geographic center of the Northern Range where it drains the northern flank of the Washburn Range before eventually flowing into the Yellowstone River. The west and east forks of Blacktail Deer Creek have drainage areas of ~35 km^2 and ~27 km^2, respectively. Blacktail Deer Plateau was glaciated multiple times most recently with the Pinedale glaciation which occurred 30,000-12,000 years ago (Fritz, Thomas 2011, Pierce K.L 1979, Licciardi J.M and Pierce K.L 2008). The Blacktail Deer creek network flows through a series of remnant glacial outwash channels that preserve kame, gravel, till, and Holocene alluvium (Pierce 1979, Fritz, Thomas 2011).

METHODS

Field

On the West Fork of Blacktail Deer Creek (WBT), we focused on classifying the bed material from the confluence to approximately 1.5 km upstream of the confluence (Fig. 1). WBT has very distinct pool and riffle morphology and we divided the reaches of pebble counts by the transition between these characteristic sections. For each pool and riffle we recorded a GPS location from the middle of the section and measured the B-axis diameter of 100 pebbles at each location. The East Fork (EBT) does not possess distinct pool and riffle morphology so instead we divided our reaches by visually assessing when the size of material noticeably changed size or approximately every 10m. On EBT we did not count an entirely continuous section but instead focused on three sections. While doing pebble counts, we focused on randomness of pebble selected and tried to avoid any accidental human bias towards selecting certain rocks over others. All pebbles were measured using a gravelometer as either 2, 2.8,4, 5.6, 8, 11, 16, 22.6, 32, 45, 64, 90, 128, 180 mm. Any pebbles that were larger than 180 mm in diameter, were measured with a ruler.

In addition to pebble counts, we also measured detailed cross sections along both forks of Blacktail Deer Creek in the same locations as the pebble counts. Surveys were performed using RTK GPS with cm-scale accuracy. We captured the cross-sectional profile of the channel approximately every 10m from the confluence upstream—on both forks. We also recorded a longitudinal profile of both forks that thoroughly captured any change in elevation between the upper reaches of each fork and the confluence.

Lab analysis

Pebble measurements were analyzed in Microsoft Excel where we calculated the D50 and D90 value for each reach on both forks. We calculated the critical shear stress needed to mobilize the sediment using the critical shear stress equation (Komar 1988):

$$\tau_t=\theta_t\,(\rho_s-\rho)gD$$

Where: τ_t=threshold flow stress, ρ_s=grain density, ρ=fluid density, g=acceleration of gravity, D=grain diameter.

To understand if Blacktail Deer Creek was able to generate enough shear stress to overcome the values we calculated for the D50, and D90—we calculated the bed shear stresses associated with a 2-year, 10-year and 100-year recurrence interval floods:

$\tau = \gamma D S w$

Where: τ=Bed Shear Stress (N/m^2), γ=Weight Density of Water (N/m^2), D= Average water depth, Sw= Water Surface slope (m/m).

We used GIS to analyze the size variability of bed material. We created a shapefile of the distinct sections where we performed counts. We than joined the pebble count data points to this shape file and color coded each section based on the D50 and D90 values so we could interpret stream wide trends in the distribution and size of bed material. A high-resolution (< 1m) DEM and orthophotograph were also used in the spatial analyses. The maps of the color-coded east and west fork will show if the sediment changes size upstream or downstream.

With the values generated from the previous equations, we compared them to shear values generated from HEC-RAS. In HEC-RAS we used the cross sections we took to model a 300cfs (8.5 cubic meters/sec) which would be approximately a 100-year flood for this stream. This model calculated the shear power in N/m^2 which we compared to the amount of shear stress that would be required to transport the sediment and therefore understand if this size flood would be capable of transporting sediment. HEC-RAS makes these calculations based on specific cross sections, so we matched these cross sections to the location of our pebble counts (Table 1).

Additionally, we analyzed the channel patterns using historic aerial photographs from the USGS in 1954 and 1969. In ArcGIS, we traced the shape of both the East and West fork on these historic images and compared them to an orthophoto from 2018. We compared the historic channel shape to the modern-day channel to better understand if and what type of transformations the stream had undergone since 1950.

RESULTS

The West fork of Blacktail Deer creek has larger average-sized sediment than the East fork with D50 values ranging from 2-180 cm and averaging at 27 cm (Fig. 2). The West fork ranges from 22.6–90 cm and averages at 62 cm. The D90 values of East Fork and West Fork are similar: 111 cm and 153 cm, respectively. Both the East Fork and West Fork show trends of increasing D50 values downstream, however, the D90 values do not show any trends on either fork.

Table 1. Sediment and flow characteristics on the west fork of Blacktail Deer Creek

Reach Number	d50 mm	d90 mm	HEC-RAS shear stress 2 yr flood (N/m2)	HEC-RAS shear stress 10 yr flood (N/m2)	HEC-RAS shear stress 100 yr flood (N/m2)	shield critical shear stress (N/m2) d50	shield critical shear stress (N/m2) d90
1	45.00	128.00	79.54	108.94	121.85	35.99*	102.36
2	64.00	180.00	57.35	105.47	152.69	52.18	146.76
3	32.00	128.00	37.78	62.75	108.28	25.09	100.35
4	64.00	180.00	79.29	94.23	105.46	52.18	146.76
5	32.00	128.00	23.30	42.12	79.18	25.09	100.35
6	45.00	128.00	52.75	75.28	77.76	35.99	102.36
7	22.60	90.00	26.63	22.52	114.22	17.01	67.74
8	64.00	128.00	73.02	94.50	26.05	52.18	104.37
9	22.60	90.00	29.58	29.06	44.22	17.01	67.74
10	64.00	128.00	50.41	93.14	82.74	52.18	104.37
11	45.00	90.00	86.06	86.90	120.54	35.99	71.97
12	90.00	180.00	21.64	28.93	73.77	74.79	149.59
13	64.00	90.00	26.37	55.42	75.71	52.18	73.38
14	45.00	90.00	27.81	30.92	78.16	35.99	71.97
15	64.00	180.00	52.34	46.36	15.83	52.18	146.76
16	90.00	128.00	68.29	75.96	76.80	74.79	106.37
17	64.00	128.00	25.77	24.27	40.58	52.18	104.37
18	90.00	180.00	64.49	42.83	114.79	74.79	149.59
19	45.00	128.00	91.21	104.58	195.91	35.99	102.36
20	90.00	214.00	55.21	69.08	107.47	74.79	177.84
21	90.00	200.00	71.96	107.26	96.08	74.79	166.21
	*transported in 2 yr flood (2.12 m^3/s)	transported in 10 yr flood (4.75 m^3/s)	transported in 100 yr flood (8.5 m^3/s)				

For the West Fork of Blacktail Deer Creek, the shields critical shear stress ranged from 17.65 N/m^2 to 70.30 N/m^2. The East Fork shields critical shear stress ranged from 1.56 N/m^2 to 99.97 N/m^2. The HEC-RAS values from the West Fork ranged from 28.56 N/m^2 to 295.10 N/m^2. After comparing the HEC-RAS modeled flood sizes of the West Fork we found that 52% of the reaches had their D50 pebbles transported in the 2-year flood, an additional 24% of reaches had D50s transported by a 10-year flood, 14% more of the reaches by the 100-year flood and 10% of the reaches had no D50s transported. For the D90 sediment, 5% of the reaches had sediment that was transported by the 2-year flood, an additional 14% of reaches had sediment transported in the 10-year flood, 19% of reaches had sediment that only became transported in a 100-year flood while 62% of all the reaches had D90 sediment that wasn't transported by any size flood (Table 1).

Analysis of the aerial photographs from 1954, 1969 and 2018 showed a relatively consistent channel shape. There was no noticeable change in channels shape between 1954 and 1969. Sometime between 1969 to 2018, the West Fork had four documented avulsions when the stream jumped its channels and

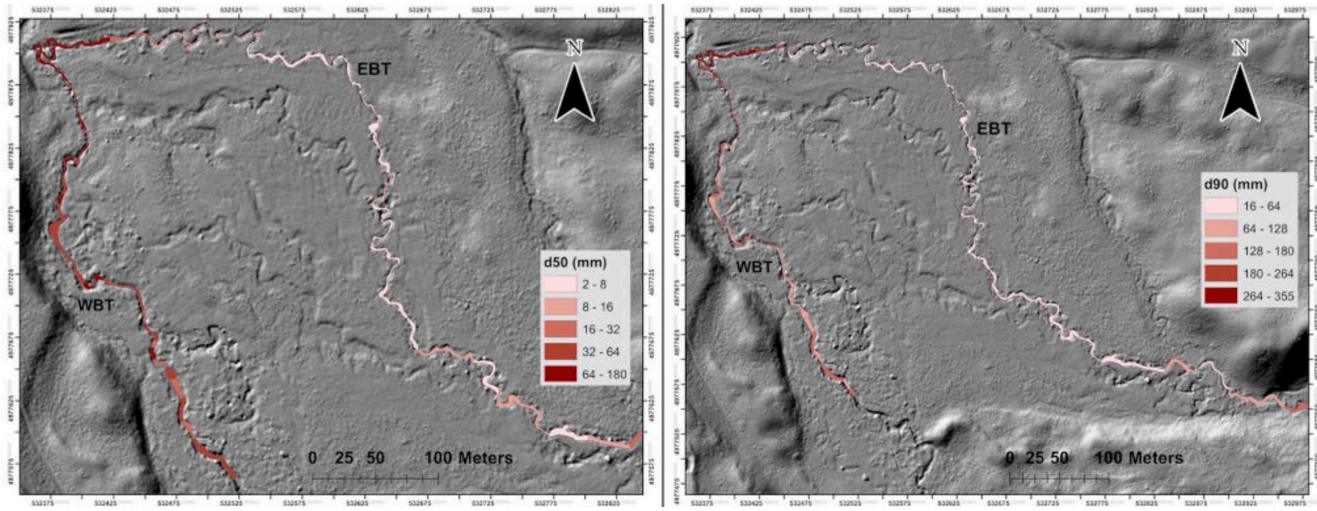

Figure 2. A) D50 values of the confluence and upstream on both WBT and EBT. The lighter color connotes smaller grain size which can be seen concentrated upstream on the East Fork. B) D90 values of the same area. The grain size in both forks becomes coarser near the confluence and the East Fork is finer overall.

cut off a meander while the East Fork had three of these same sized movements. From these photos, the channels have remained consistently the same shape with the exception of the few meter-long sections where avulsions have occurred. There have been channel avulsions in both forks since the 1950s (Figure 3).

DISCUSSION AND CONCLUSION

Bed shear stresses compared with the critical shear stress of the D50 and D90-sized pebbles in the West fork are used to determine if channel bed sediment is mobilized during different size floods. A 2-year flood is the typical bankfull flood that is associated with channel form (Wolman, Leopold 1957). Even in this regular size flood, less than 50% of the reaches had D50 pebbles transported. This suggests that this stream is not capable of transporting significant amount of the bed sediment and thus has limited ability to shape the channel during high frequency floods. Even in a very large, 100-year flood, 20% of the D50 sized pebbles would remain in place. Sediment downstream takes larger floods to transport than the sediment found upstream suggesting that the smaller floods have been incrementally transporting larger sediment downstream where it sits until a larger flood comes.

The geomorphic history of the stream system is an important control on modern channel form and process. Blacktail Deer Creek is superimposed on glacial till, outwash, and kame deposits from the Pinedale glaciation (Pierce 1979). Following the retreat of this glacier approximately 12,000 years ago (Licciardi, Pierce 2008) there was an extensive period of sedimentation as a result of the over steepened, glaciated slopes that were prone to mass movements. An extensive terrace on both the east and west forks likely formed due to the increased rates of sedimentation. In the field, we identified an ash layer from the Glacier Peak volcanic eruption approximately 11,000 years ago in this terrace indicating aggradation in the early and middle Holocene. Subsequently and there was a decrease in the sediment load of Blacktail Deer creek which likely lead to a period of incision. Eventually, much of the sediment was eroded away leaving distinct terrace and the channels of Blacktail Deer creek. As the stream incises into the Holocene fill its limit for incision is controlled by the local base level of the underlying glacial till. This is all supported by the trend in increasing D50 values moving downstream which leads to increased shear stresses which are more difficult to overcome in flooding events. These over steepened slopes referred to earlier were located upstream in the Washburn Range and was eroded more quickly further from the source.

The analysis of air photos from 1954, 1969, and 2018 indicate that the channel is relatively stable except where there were seven channel avulsions sometime between 1969 and 2018 (Figure 4). As shear stresses

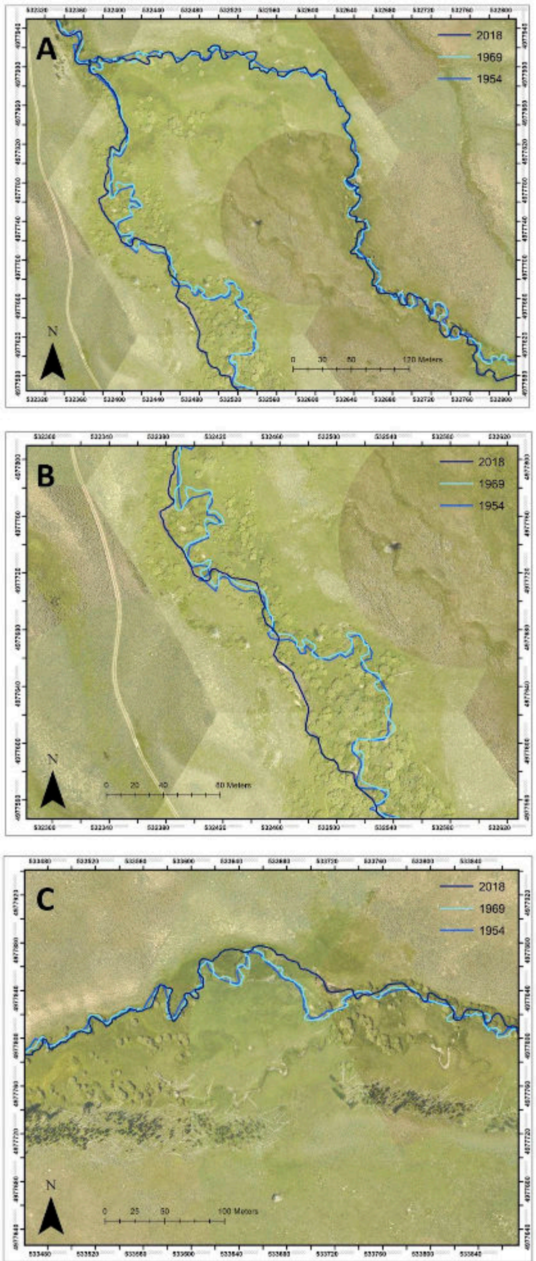

Figure 3. A) Confluence and upstream, shows a relatively stable and consistent channel shape from 1954 to 2018. B) zoomed in view of an avulsion since 1969 on WBT. C) zoomed in view of a slight avulsion since 1969 on EBT, also shows paleo channels that seem to have been abandoned since at least 1954.

are relatively low during large floods, it is unlikely that these avulsions are a product of incision of the channel bed but more likely the product of channel filling and cutting into fine-grained floodplain deposits. Blacktail Deer Creek has experienced a period of aggrading since during the early and middle Holocene. During this time, Blacktail Deer Creek aggraded mostly with smaller diameter sediment that mantles coarse remnant glacial outwash and till. The historical aerial images show the stream to be generally contained within

Figure 4. Photographs of the west and east forks of Blacktail Deer creek from the 2019 field season. Circled in red are the examples of large diameter relict till and kame gravels. The sediment is in the channel and is too large to be transported by modern flood discharge and instead has been in place since the formation of the creek and provides armor for the channel that limits net channel incision.

its channel and does not seem to be incising new meanders.

By our detailed documentation of the sediment character in Blacktail Deer Creek, we are able to have a better understanding of the fluvial dynamics of the stream. From extensive pebble counts, we have a thorough characterization of the bed material and we have determined that the shear stresses associated with flooding events are not sufficient to mobilize the channel bed and trigger relatively quick incision in the second half of the 20th century. Due to the large diameter sediment present in both forks, this stream has been relatively stable in the historical period. While the willows have been affected by the over grazing of large ungulates in the Northern Range it is unlikely that abundance of riparian vegetation has played a significant rule in the evolution of this stream given that it is heavily controlled by large diameter relict till. The geomorphic controls are a significant control on the morphology and channel history of Blacktail Deer Creek.

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