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Channel Response to Flow Augmentation: Diamond Fork River, UT

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CHANNEL RESPONSE TO FLOW AUGMENTATION:

DIAMOND FORK RIVER, UT

by

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in

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ABSTRACT

Channel Response to Flow Augmentation: Diamond Fork River, UT

by
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Utah State University, 2023

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A river's physical features—such as slope, width, and pattern—depend on the water and sediment supplied to it. The Diamond Fork River, located in central Utah, provides an exceptional opportunity to explore the response of a river to an increase in river flow. Trans-basin flow diversions larger than the typical natural flood were delivered to the Diamond Fork over the irrigation season for 87 years (1916-2003).

Our project goals were to describe 1) channel response to this large and long artificial flow augmentation and 2) how the channel recovered after the removal of the diversion flows. We use aerial photographs to document channel conditions throughout the 20th century.

This work builds on that of (Jones, 2018) by increasing the temporal resolution of the analysis with additional air photos taken in the 20th century. Further, we isolate locations abandoned by the river to determine the river elevation at different times in the past. We also expand both spatial and temporal resolution and scope for the post-diversion history of the river to inform decisions about river management.

We find that channel response to the trans-basin diversion flows depends on valley confinement, with more vertical adjustment in confined reaches and predominantly lateral adjustment in unconfined reaches. Two floods larger than the diversion flows produced different impacts. The first flood incised through earlier deposits and widened the channel. The second flood produced widening but little incision. Both large floods were followed by a recovery period during which the channel narrowed. Following the removal of diversion flows, the channel has continued to narrow and form meander bends at a smaller scale.

(146 pages)

PUBLIC ABSTRACT

Channel Response to Flow Augmentation: Diamond Fork River, UT

Diane Elizabeth Wagner

A river's physical features and channel dimensions are determined by the water and sediment supplied to it. The Diamond Fork River, located in central Utah—received large trans-basin diversion flows from 1915-2003, providing an exceptional opportunity to explore the response of a river to a large increase in flow.

Our project goals were to describe 1) channel response to this large and long artificial flow augmentation and 2) how the channel recovered after the removal of the diversion flows. The objective of this thesis is to document the channel condition throughout the 20th century to present day as a basis for describing the impact of flow augmentation on channel change and for guiding future river management.

This work builds on the findings of (Jones, 2018) by adding resolution to the 20th century changes with additional historic air photos. We also add information on historic river channel elevation by studying locations that the river abandoned in the 20th century. We find the extent and nature of channel adjustment depends on whether the valley is narrow or wide. Floods larger than the diversion flows produced channel change followed by a recovery period that allowed the channel to narrow. After diversion flows were removed from the river in 2004, the river channel continues to narrow, form meander bends, and riverbank vegetation has begun to hold the channel in place.

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CHAPTER 1

20th CENTURY CHANNEL RESPONSE TO LARGE FLOW AUGMENTATION

1. Introduction

Rivers adjust their channels based on the supply of water and sediment, moderated by the interactions with bedrock that constrain valley width and the influence of vegetation and humans. Changes in water and sediment supply impact the river's physical features that include slope, bed texture, planform, cross sectional dimensions, and floodplain characteristics. Understanding the nature of these adjustments – their controls, mechanisms, and rates—helps explain how and why a channel changes (Lane, 1955; Leopold and Wolman, 1957).

An increase in river discharge, whether by climate change or human interaction such as trans-basin diversion, can produce extensive channel change. It has been documented that increased flow in Lake Fork and La Poudre Pass Creek in Colorado widened the channels, decreased the total riparian vegetation cover, increased channel slope by shortening the meander distance, increased the channel depth due to changes in slope, as well as coarsened the bed material, therefore increasing bed roughness (Abbott, 1976; Dominick, 1997; Kellerhals et al., 1979; Wohl and Dust, 2012). Kellerhals et al. (1979) established that in bedrock systems, a channel's response to flow augmentation depends on the bedrock strength and the valley geometry, however, self-formed channels in alluvium are influenced by the type of bed and bank material and the valley slope. The magnitude of the augmented flows caused a varied response for alluvial channels. Smaller magnitudes can increase the channel width and larger increases can cause the channel to shift from meandering to braided. In response to a diversion that increased the summer mean monthly flows by a factor of three, Bradley and Smith (1984) documented channel widening and an increase in the channel migration rate on the Milk River, Alberta.

A river's bed and channel dimensions at any given time reflect a combination of past disturbances, such as floods and changes in water and sediment supply, how the channel recovers from these disturbances, and its current conditions. The impact of humans on geomorphic landscapes, such as through dam construction and the addition or depletion of trans-basin diversion flows, has been a large factor that has altered the hydrology and sediment supply of many rivers (Buffington, 2012; Church, 1995; East et al., 2018). A variety of watershed features that control river morphology include valley slope and confinement; discharge, sediment supply, and vegetation (Buffington, 2012). Understanding how rivers change in response to human activities such as flow augmentation, natural disturbances, such as floods, and vegetation is essential for river management and restoration. Flow augmentation can also be considered an analogue for increased flood flows and increased total flow associated with climate warning. Although drying is occurring in the intermountain west (Wise, 2012), other parts of the world are experiencing greater runoff and floods (Hirabayashi et al., 2013). Therefore, understanding how a river channel responds to large flows can help inform the impacts of those changes.

The impact of flow augmentation should be assessed in context of the natural flow regime, which includes larger natural floods whose impacts must be distinguished from the effects of the augmentation. The Kemano River in the British Columbia Coast Mountains provides an illustration of the role natural floods can play on rivers with artificial flow augmentation (Church, 1995). In this study, augmented flows were not sufficient to incise the coarse bed. In the absence of bed incision, the increased mean annual flow promoted channel widening and made the river more susceptible to planform change when a large natural flood occurred. Because the sediment supply was not altered, the channel widened since the discharge increased and sediment was redistributed, promoting erosion of the channel banks. Following a natural flood of sufficient magnitude to mobilize the bed that occurred 20 years after the introduction of diversion flows, this led to incision and channel narrowing through sediment deposition on the channel edge (Church, 1995). Thus, augmented flows over 20 years widened the channel but did not erode the coarse bed. The river accommodated the additional flow by eroding the banks of channel-islands and the channel edge, which were more prone to erosion

(Church, 1995). After the channel bed mobilized in the flood, general degradation began, and the river began to approach its predicted post-diversion flow regime resulting in the abandonment of bar surfaces that had developed over the previous 20 years (Church, 1995). The Kemano River demonstrates a case in which the full effect of flow augmentation appeared only after the occurrence of a natural flood.

The Lane balance provides a starting point for understanding river channel change, demonstrating an indication of sediment deficit or surplus (Lane, 1955). This balance demonstrates that water discharge and channel slope are proportional to the sediment supply and the grain size of the sediment supply (Lane, 1955). It also suggests that as the variables of water, sediment supply, or grain size of the supplied sediment are modified, the elements that support the balance adjust to accommodate this change (Lane, 1955).

Channel response to flow augmentation will differ depending on whether the flow augmentation produces a condition of sediment surplus or deficit (Henderson, 1966; Lane, 1955; Schmidt and Wilcock, 2008). Sediment deficit may lead to either channel widening or channel deepening (Bradley and Smith, 1984). Channel widening is favored when the channel bottom is bedrock or armored, thereby limiting incision (Bradley and Smith, 1984; Church, 1995). Sediment surplus can lead to bar deposition, increased rates of erosion on meander bends, and increased rates of lateral channel migration (Bradley and Smith, 1984). This increase in sediment can also lead to deposition or erosion, avulsion, and change in channel pattern (Bradley and Smith, 1984).

Short-term channel response to flow augmentation includes changes in texture and channel bed configuration. Under conditions of sediment surplus, the bed may become finer grained and more mobile, which increases the transport capacity (Schmidt and Wilcock, 2008). Sediment deficit, on the other hand, may coarsen the channel bed (Johnson et al., 2015; Schmidt and Wilcock, 2008). The mechanism responsible for an increase in sediment transport capacity is surface fining that then causes a decrease in critical shear stress (Johnson et al., 2015; Wilcock and Crowe, 2003). Sediment surplus or deficit can also be used to evaluate changes in channel topography. An increase in sediment supply can produce a decrease in topographic variation, smoothing the bed and enhancing sediment mobility whereas a decrease in sediment supply can increase topographic variation, decreasing sediment mobility (East et al., 2018).

Channel response to flow augmentation over longer time scales can include changes in width, slope, channel pattern, and sinuosity. The hydraulic geometry, based on many observations of channel dimensions, indicates that channel width increases in proportion to the square root of a characteristic discharge (Leopold and Maddock Jr., 1953). However, sediment supply is not included in this statement. Schumm, (1969) proposed that with an increase in river discharge, channel width, depth, and meander wavelength will increase, and channel slope will decrease. An increase in the rate of sediment supply will increase channel width, meander wavelength, and channel slope while channel depth and channel sinuosity will decrease. Channel slope is another attribute that adjusts on a slower timescale with changes in water and sediment supply. In general, a steeper channel slope increases the transport capacity since a steeper channel slope eases the movement of sediment (Kellerhals et al., 1979).

Channels can still be influenced by natural floods if these floods are larger than the augmented flows. Rapid fluctuations in discharge and greater flow volume are two characteristics of augmented flow that likely facilitate bank erosion and channel widening (Wohl and Dust, 2012).

The Diamond Fork River (DFK), located in central Utah (Figure 1.1), provides an exceptional opportunity to explore the response of a river to a large artificial flow augmentation over a geomorphically significant amount of time of almost 90 years.

After the completion of the Strawberry Tunnel in 1915, water from the Uinta Mountains in the Green River drainage was introduced to Sixth Water Creek, a tributary of the Diamond Fork River. The water then flowed through the Diamond Fork River to provide irrigation water in Utah Valley. The augmented flows were highly erosional in Sixth Water Creek (SXW), causing

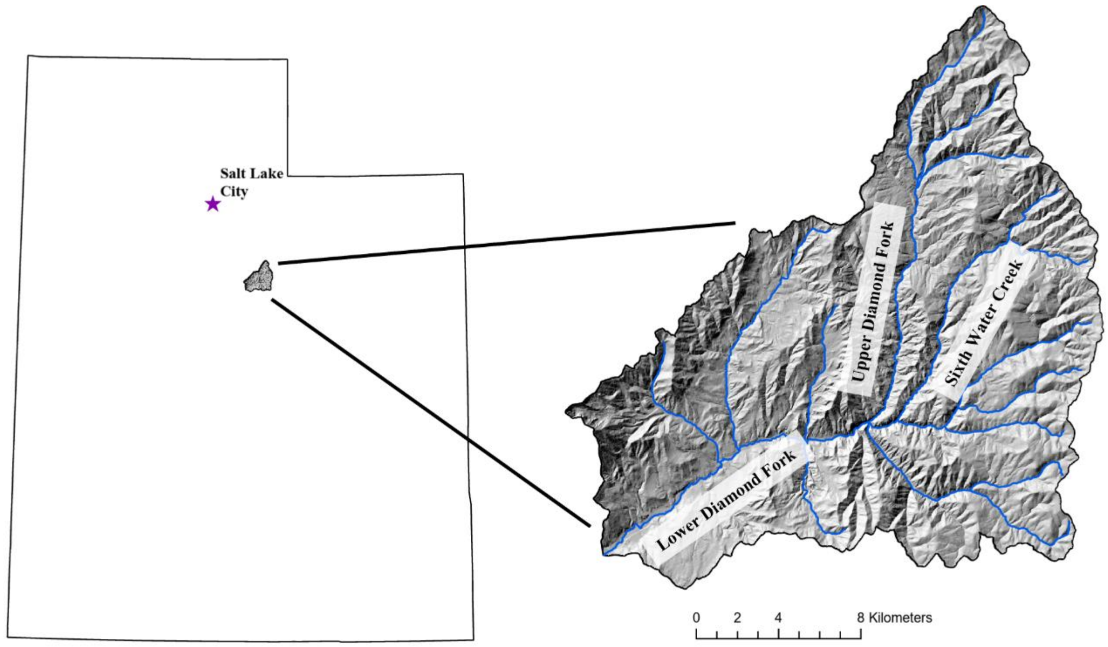

Figure 1.1. Location map of the Diamond Fork watershed in Utah, USA.

deep incision and delivering sediment to the Diamond Fork River (Jones et al., 2023). The volume of sediment coarser than 8 mm delivered from Sixth Water Creek to the lower Dimond Fork over the life of the augmented flows was estimated to be 400,000 m^3 (Jones et al., 2023). It is not likely that all of this sediment was retained by the lower Diamond Fork (LDFK). If half the evacuated sediment were retained, the channel bed of the lower Diamond Fork would aggrade by 0.5 m (Jones et al., 2023). We suspect that sediment supply from Sixth Water Creek was at a maximum during the first years of the diversion project, beginning in 1915. This is consistent with reports of excessive deposition and road damage in the upper reaches of the lower Diamond Fork in the first years of the project. The rate of sediment delivery from Sixth Water Creek should decrease with time. Although details on the rate of decrease is not available, it is likely that the rate of sediment delivery from Sixth Water Creek was much reduced 37 years into the project, when the first major flood occurred in 1952 (Jones et al., 2023).

In the case of dam removal, a very large increase in sediment delivery has been found to cause extensive channel change and aggradation of the riverbed (East et al., 2018). The large sediment pulse from SXW in the beginning of the project period likely caused channel aggradation on the lower Diamond Fork. As the rate of sediment supply decreased in later years, the river could cut into alluviated deposits leaving relict surfaces visible in the first available air photo in 1939. The existence of such relict and their elevation above the modern channel play a key role in developing the history of channel change in response to flow augmentation.

In 1992, the Central Utah Project Completion Act (CUPCA) mandated that the augmented flows were to be removed from the river and re-directed through a series of pipes and tunnels (United States Congress, 1992). The flows diverted from Strawberry Reservoir were then passed through the new Syar tunnel and introduced lower on Sixth Water Creek in 1996. The building of the pipes and tunnels was completed in 2004, resulting in the trans basin diversion flows bypassing the entire Sixth Water/Diamond Fork drainage (Figure 1.2).

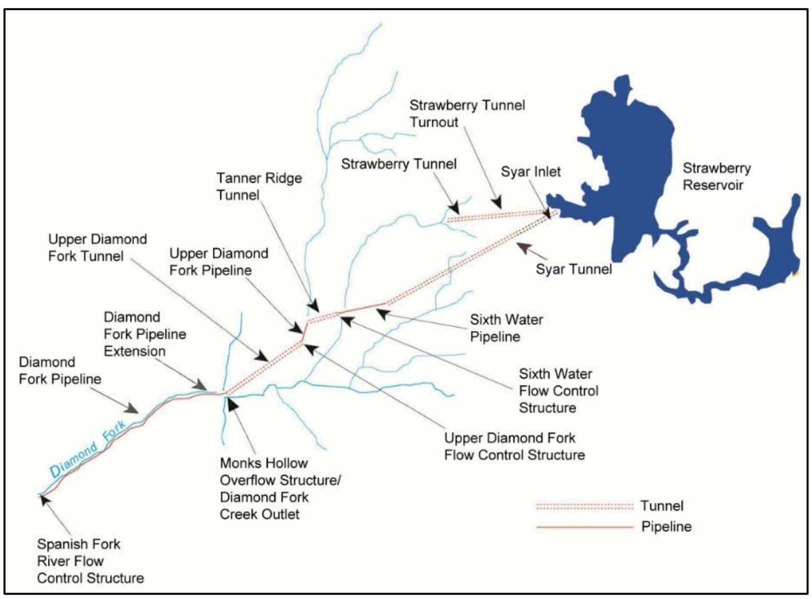

Figure 1.2. Map displaying components of the Diamond Fork water delivery system. Map posted online by U.S Department of the Interior.

Two large natural floods occurred during the 1916-2003 diversion period. These large floods of approximately 1,500 ft^3/s in 1952 and approximately 2,500 ft^3/s in 1984 caused significant channel change and channel widening. These two floods were three to five times larger than the augmented flows and thus could play an important role in the longer-term channel response to flow augmentation. There have been few studies that document how rivers respond to such large and sustained increases in discharge, providing an exceptional opportunity to evaluate river channel change in response to flow augmentation. The magnitude, duration, and history of the diversion flows in the Diamond Fork Watershed provides an example to document channel change through understanding the impact of a large and long artificial flow augmentation in addition to understanding how a large sediment pulse from Sixth Water Creek impacted the channel during the early years of the augmentation period.

Previous research in the Diamond Fork watershed (Jones, 2018; Jones et al., 2023) examined the response of both Sixth Water Creek and the lower Diamond Fork River to this large artificial flow augmentation. On lower Diamond Fork specifically, general incision and channel widening was reported. These studies concluded that LDFK channel response depended on valley confinement and slope, channel constrictions, and vegetation establishment. Back-and-forth shifts in channel width and channel pattern were also described, meaning that the channel fluctuated from widening to narrowing and from single thread to braided over the augmentation period. These back-and-forth shifts suggest not only progressive change in response to the diversion flows, but shorter-term response to natural floods. This project expands on this work on the lower Diamond Fork in particular, adding a finer temporal and spatial resolution to the analysis along with new information on historical channel elevation to tell a more complete story of channel response to flow augmentation.

2. Study Area and Reach Description

The lower Diamond Fork River (LDFK) begins at the confluence with Sixth Water Creek (SXW) and extends 18.5 km downstream to its confluence with the Spanish Fork River (Figure 1.1). This mountainous watershed drains 400 km^2 in the Wasatch Mountains of central Utah. This watershed is primarily in Mesozoic sedimentary rocks with terraces, alluvial fans, and landslide deposits that line the channel in some areas.

Along this river, bed material and transport rate increases downstream as the grain size decreases (Wilcock et al., 2019). Previous studies found that the most active sediment transport was in the downstream reaches around 13.5 km to 18.5 km downstream from the confluence with Sixth Water Creek (Jones, 2018; Jones et al., 2023; Wilcock et al., 2019). The bed material throughout the LDFK can be considered partially mobile (Jones et al., 2023; Wilcock and McArdell, 1993, 1997).

Spring snowmelt dominates the natural hydrograph of the Diamond Fork Watershed. Trans-basin water was delivered to the Dimond Fork watershed through Strawberry Tunnel, which was completed in 1913 with flow releases beginning in 1915 (United States Bureau of Reclamation, 1916). This tunnel delivered water from Strawberry Reservoir directly into Sixth Water Creek, where it then joins the Diamond Fork River 16 km downstream from Strawberry Tunnel (Figure 1.2). Water from Strawberry Reservoir produced flow diversions of 400 ft^3/s – 500 ft^3/s that were common during the peak of the growing season between May and September (Jones, 2018; Jones et al., 2023). These flows greatly exceeded the natural summer flows as well as the peak natural runoff for most years (Figure 1.3).

Based on a 43-year record in the mid to late 20th century compiled by Jones et al. (2023), the daily mean flow on LDFK exceeded 500 ft^3/s about half of the years and exceeded 350 ft^3/s on average 33 days per year. Flows of 500 ft^3/s surpass the natural 2-year flood by a factor of 3 at the confluence with Sixth Water Creek and by a factor of 2 at the outlet of Diamond Fork River, at its confluence with Spanish Fork River. Flows of 350 ft^3/s surpass the natural 2-year flood by a

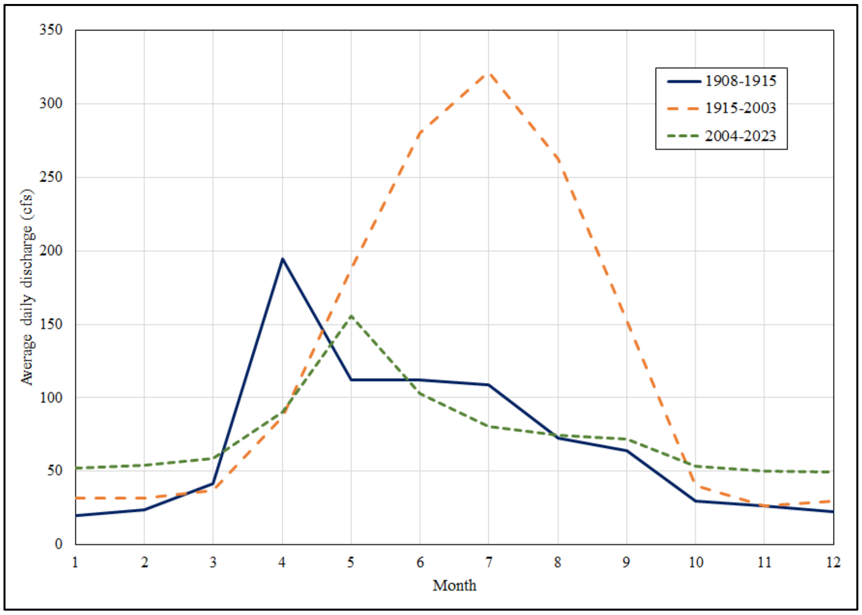

Figure 1.3. Average daily mean discharge (ft^3/s) for Diamond Fork River. The time periods represent pre-augmentation (1908-1915), the period of high flows transported in the channel (1915-2003), and the period with mandated base flows (2004-2023).

factor of 2 downstream of the confluence of Sixth Water and Diamond Fork by about 1.4 times at the outlet of the Diamond Fork watershed (Jones et al., 2023). Typically, no flows were released between October and April, therefore causing the winter flows from 1915-1997 to be similar to the natural flow regime (Jones, 2018; Jones et al., 2023).

A series of pipelines and tunnels were constructed to carry the trans-basin diversion flows and bypass Sixth Water Creek and Diamond Fork River (United States Congress, 1992). In 1996, Syar Tunnel was completed to transport water from Strawberry Reservoir to an outlet approximately 10 km downstream from Strawberry Tunnel (Figure 1.2). Syar Tunnel became operational in 1997, allowing diversion flows to bypass upper Sixth Water Creek. In 2004, the Diamond Fork Tunnel and pipeline system became fully functional which allowed the diversion flows to entirely bypass the river channel. In addition, minimum instream flows were mandated to support fish and wildlife resources (United States Congress, 1992). Two flow controls, one on Sixth Water Creek at Syar Tunnel and one at Monk Hollow Outlet, located 12 km upstream from the mouth of the Diamond Fork River, were included in the construction of the tunnel and pipeline system.

Mandated flows are met by releasing water from Strawberry Tunnel, Syar Tunnel Outlet, and Monks Hollow Outlet. On Diamond Fork, the mandated minimum flow is 80 ft^3/s from May 1 to September 30 and 60 ft^3/s from October 1 to April 30. These flows exceed the natural base flow on lower Diamond Fork by a factor of 6 (Jones et al., 2023). Figure 1.3 displays the average daily mean discharge (ft^3/s) for the Diamond Fork River in three different time periods: 1908-1915 before trans-basin diversions, the flow diversion period 1915-2003, and 2004-present after the diversion flows were removed from the river and minimum baseflows are implemented.

Jones (2018) delineated four process domains on LDFK using the River Styles Framework—a process-based method to distinguish river segments (Brierley and Fryirs, 2004). The two upstream LDFK process domains (5 and 6) have a gravel and cobble bed with the channel frequently constrained by bedrock valley walls, roads, and alluvial fans. Process domain 6 is defined by the addition of flow from the Monks Hollow Outlet with much of the reach lined by a narrow corridor of large cottonwood trees. A lower slope with finer grain sizes and extensive campground infrastructure defines process domain 7. The bed material in this domain is primarily gravel with cobbles and some fines. Process domain 8 incorporates the most downstream 8,100 m of the Diamond Fork immediately upstream of Highway 6 and the confluence with Spanish Fork. This part of the river has the lowest slope, the finest grain size, and the least confinement provided by terraces, alluvial fans, and an inactive landslide. The bed material in this domain is primarily medium to coarse gravel.

To provide a greater spatial resolution to examine channel change, we define 13 reaches based on valley confinement and channel gradient and pattern (Figure 1.4, Figure 1.5). The 13 reaches are described from upstream to downstream. Table 1.1 presents the average channel slope for the 13 reaches as well as an estimate of the average valley bottom width, sinuosity, and the

Table 1.1. Channel slope, confinement, D_{50}, and D_{84} for reaches 1-13 and how they correspond to the process domains delineated by Jones (2018). DC – Dry Canyon, BDC – Below Dry Canyon, MH – Monks Hollow, RL – Red Ledges, DCG – Diamond Campground, BBH – Below Brimhall Bridge, LV – Levee, MO – Motherlode, UOX – Upper Oxbow, LOX – Lower Oxbow, U&LCH – Upper and Lower Childs. D_{50} and D_{84} were based on the findings of Jones (2018) on LDFK.

Process Domain Number (Jones, 2018)	5		6			7	8					
Reach Number	1	2	3	4	5	6	7	8	9	10	11	12 & 13
Reach Code Name	**DC**	**BDC**	**MH**	**BMH**	**RL**	**DCG**	**BBH**	**LV**	**MO**	**UOX**	**LOX**	**U&LCH**
Channel Slope	1.5%	1.5%	1.1%	1.3%	1.0%	0.9%	0.7%	0.6%	0.6%	0.7%	0.6%	0.5%
Avg. Valley Bottom Width (m)	56.9	45.7	75.4	64.6	86.3	129.5	96.4	151.8	275.2	188.1	246.3	221.3
Sinuosity	1.13	1.06	1.09	1.10	1.14	1.12	1.16	1.17	1.42	1.26	1.40	1.19
D_{50}	45	45	45	45	45	45	45	45	22.6	22.6	22.6	22.6
D_{84}	90	90	64-90	64-90	64-90	64	64	64	45	45	45	45

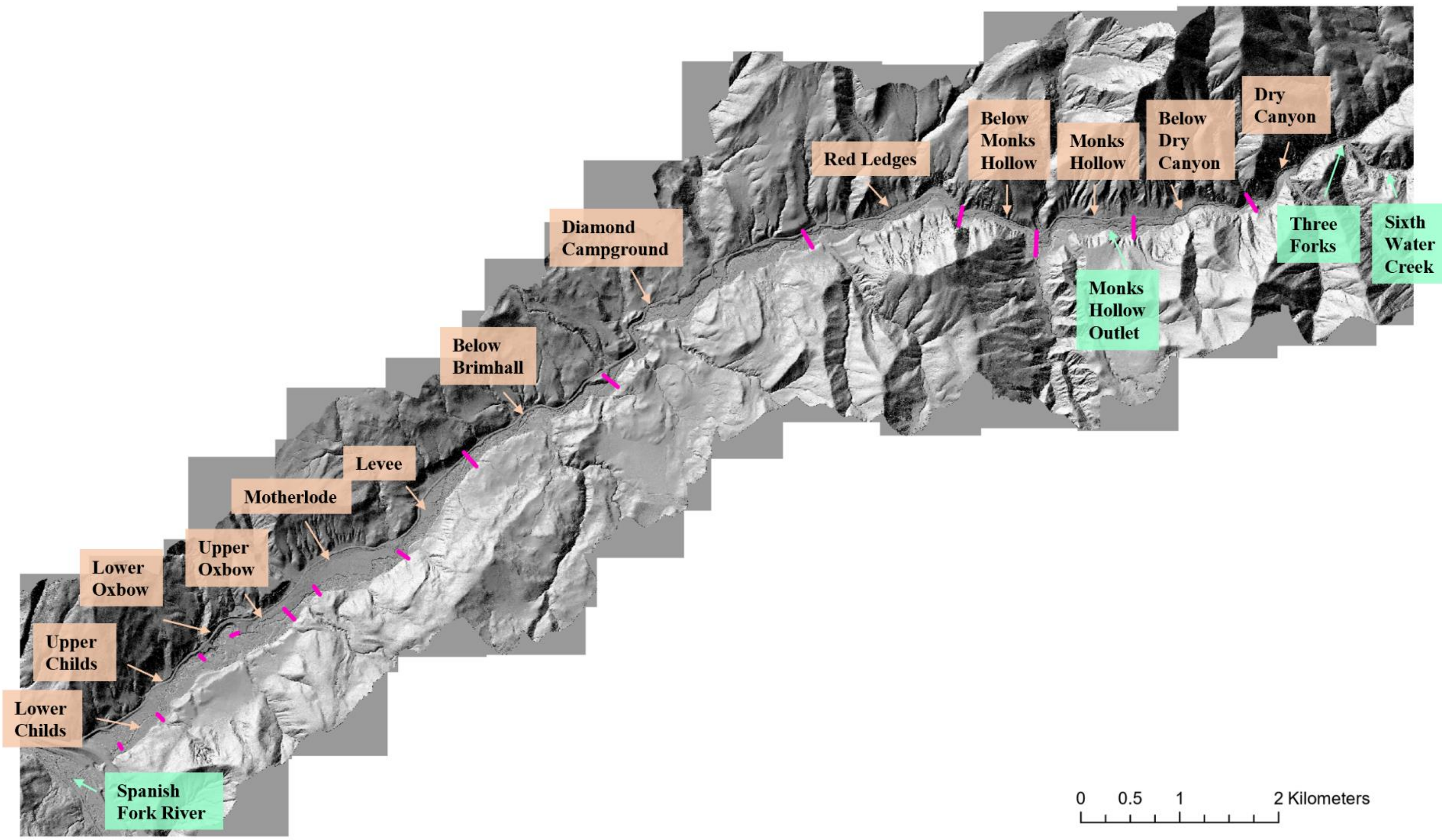

Figure 1.4. Locations of 13 reaches designated for the lower Diamond Fork River displayed on 2017 hillshade.

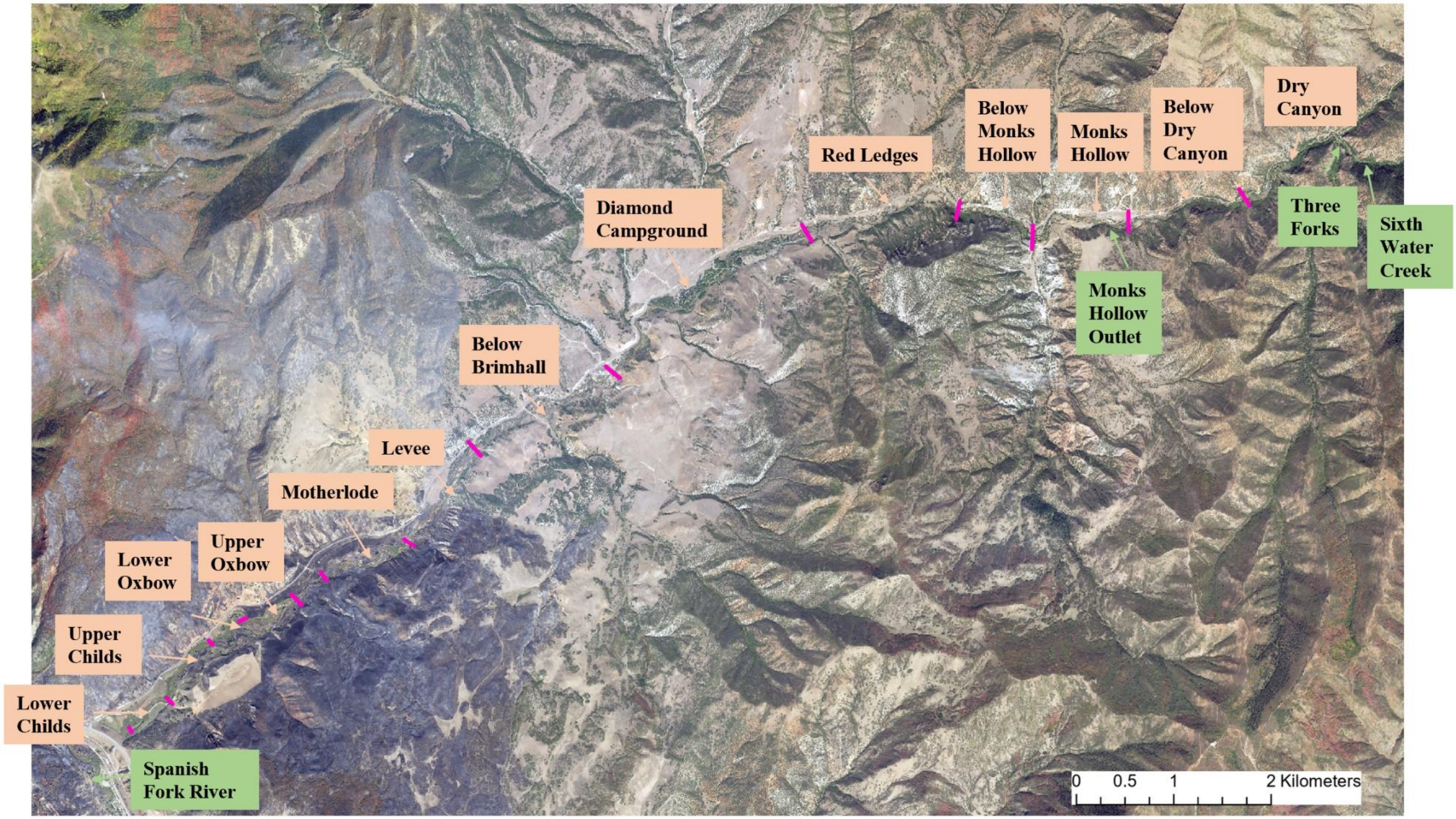

Figure 1.5. Locations of 13 reaches designated for the lower Diamond Fork River displayed on 2018 NAIP imagery.

median (D_{50}) and 84th percentile bed grain size (D_{84}) based on pebble counts reported by Jones, (2018).

Reaches 1 through 4—Dry Canyon, Below Dry Canyon, Monks Hollow, and Below Monks Hollow—are largely confined between alluvial fans and bedrock walls and further constrained by the Diamond Fork Forest Road. These reaches encompass Process Domains 5 and 6 as delineated by Jones (2018). The stream slope in these reaches is steep, the riverbed is coarse gravel/cobble, and the channel has low sinuosity in the present regime (Table 1.1). The channel is largely single thread, except in Dry Canyon where a broad braid plain occupied the entire valley bottom early in the project period.

Reach 5, Red Ledges is largely confined by alluvial fans and bedrock valley walls and further constrained by the Diamond Fork Forest Road. This reach is part of Process Domain 6 as delineated by Jones (2018). Red Ledges has a shallower slope compared to the upstream reaches and the channel is largely single thread with low sinuosity (Table 1.1). The riverbed is gravel and cobble in the present regime. Downstream of Reach 5, the valley setting opens to be mostly unconfined.

Reach 6, Diamond Campground contains the largest US Forest Service campground, which was built in the early 1960s. This reach encompasses Process Domain 7 as delineated by Jones (2018). This reach has a shallower slope than the upstream reaches (Table 1.1) and is largely unconfined but occasionally constrained by the Diamond Fork Forest Road and local terraces. The channel has low sinuosity (Table 1.1) and is mostly single thread with sections of braiding that have been present throughout the study period. The riverbed is coarse gravel in the present regime.

Reaches 7 through 13 have the lowest slope, the finest grainsize, with only alluvial fans and terraces confining these reaches. This encompasses Process Domain 8 as delineated by Jones (2018). The riverbed in the present regime in this section of the LDFK is medium-coarse to coarse gravel. The channel in Reach 7—Below Brimhall Bridge—has low sinuosity (Table 1.1) and is largely single thread although there have been sections of braiding throughout history. Brimhall bridge was burned by the Pole Creek fire in 2018 and has not been rebuilt. Sections of the river channel corridor were burned from the downstream section of the Diamond Campground reach (Reach 6) through the upstream section of the upper and lower Childs reaches (Reaches 12 and 13).

Much of the reach 8—Levee—was a broad braid plain from 1939-1997. This reach has low sinuosity (Table 1.1) and although a single thread channel developed towards the end of the diversion period, the braid plain is still largely intact. A levee was constructed following the 1984 flood to steer the channel away from the Diamond Fork Forest Road.

Much of Reaches 9, 10, and 11—Motherlode, upper Oxbow, and lower Oxbow—was occupied by a broad braid plain from 1939-1997. Although a single thread channel developed towards the end of the diversion period, the braid plain is still largely intact and has slowly become vegetated in the post-diversion period. The channel in the Motherlode and lower Oxbow reaches is sinuous, demonstrating that there is room for lateral movement, whereas the modern channel in upper Oxbow has low sinuosity (Table 1.1).

Reaches 12 and 13, upper Childs and lower Childs are the furthest downstream reaches and have the lowest slope (Table 1.1). The distance from the bottom of the reach to the confluence with Spanish Fork River is roughly 0.6 km. Delta deposition was present in the early flow augmentation years, which was possibly augmented by a large pool created by incomplete construction work for the railway bed along Spanish Fork. Construction of the Rt 6 embankment in 1983 eliminated the lower 0.23 km of the reach and established a new base level that continues to present. The channel has low sinuosity and is largely single thread and has been that way throughout the project period.

3. Methods

The focus of this research is to describe the LDFK channel condition – width, pattern, texture, and elevation – over the 1915-2003 period of flow diversion. Of particular interest are surfaces that were created by the channel and subsequently abandoned by the river. The relict surfaces provide evidence of channel elevation at the time they were abandoned. Candidate relict surfaces were initially identified based on channel position observed in historical air photos and then delineated on a 2017 LiDAR DEM. The surfaces were identified on the DEM to account for channel shifting after the last air photo in which the surface is seen in the channel. The first air photo is from 1939, 23 years after the start of the diversion flows. Field visits were made to observe the grain size and elevation of abandoned surfaces and to evaluate possible modifications after the surface was no longer part of the active channel, therefore abandoned.

3.1 Abandoned Surface Identification

Relict surfaces were identified from the sequence of air photos (Table 1.2) and from a Digital Elevation Model (DEM) developed from LiDAR topography flown October 3-6, 2017 by the National Center for Airborne Laser Mapping (Jones, 2018). Abandoned surfaces were labeled by the year of the last photo on which the surface was in the active channel. Each candidate relict surface was evaluated for later occupation by the active channel and for clues regarding post-abandonment modification. The active channel was defined to include both the visibly wetted channel as well as areas of bare sediment next to the wetted channel. This definition was influenced by the resolution of the historical aerial photos and to use the same method as Jones (2018). The active channel boundary was generally determined as the boundary between vegetation and adjacent water or bare sediment. This approach allows for certainty in the channel delineation at the expense of including multiple geomorphic surfaces (e.g. floodplains, bars, wetted channel) within the "active" channel. Final editing of mapped relict surfaces was based on the 2017 DEM such that each surfaces contained a contiguous area with a small range in

Table 1.2 Dates and sources of available aerial imagery including the discharge of the Diamond Fork River on the date the imagery was taken. The discharge stated for the 1981 and 1982 imagery was from the *Spanish Fork at Castilla, UT* gage.

Year	Source	Scale/Resolution	Color	Flight Date(s)	Discharge at active gage (cfs)
1939	Soil Conservation Service	1:30000	B&W	7/21	278
1953	Army Map Series	1:63000	B&W	8/4	42
1956	USGS	1:20000	B&W	7/16, 7/23	269
1964/5	UGS	1:15840	B&W	1964: 8/18, 8/24, 8/30, 9/10. 10/6/65	245 – 1964 107 – 1965
1971	UGS	1:15840	Color	7/28, 7/31, 8/9, 8/10, 8/11, 9/1	364
1981	UGS NHAP	1:40000	False Color	9/11	73 @ Castilla
1982	NHAP	1:40000	False Color	9/23	153 @ Castilla
1983	NHAP	1:40000	False Color	9/5	149
1984	UGS	1:12000	Color	9/17	104
1993	USGS DOQQ	1:40000	B&W	8/17, 8/23, 8/24, 8/28, 9/9	399
1997	DOQQ	1:40000	B&W	7/8, 9/30, 10/4, 10/5	Varies: 238 SXW-Dry; 377 MHO-DCG; 27 DCG-CH
2003	NAIP	2 m	Color	8/31, 9/3	211
2004	NAIP	1 m	Color	8/28	84
2006	NAIP	1 m	Color	8/26, 8/28, 8/31, 9/2, 9/3	91
2009	NAIP	1 m	Color	7/10, 8/10	82
2011	NAIP	1 me	Color	8/6	86
2014	NAIP	1 m	Color	8/11, 9/3	82
2016	NAIP	1 m	Color	8/2, 8/19	46
2018	NAIP	0.6 m	Color	9/11, 9/26, 9/27	60
2018	Google	15 cm	Color	9/10	56.4
2021	Hexagon	15 cm	Color	9/23	40.6

elevation. We are able to associate the surfaces with a particular time interval between air photos, but we are not able to assign a particular geomorphic process to the mapped surfaces.

In total, 304 relict surfaces were identified as fluvial with time of abandonment from before the first aerial image (1939) to the removal of diversion flows in 2004. In addition to ensuring that the surface was not reoccupied by the river at a later time, the 2017 topography of each surface was evaluated in detail to help delineate the surface and evaluate its formative process.

The basic spatial analysis information – LiDAR DEM, aerial photographs, mapped relict surfaces, and active channels, as well as metadata concerning the mapped surfaces are available in the digital archive *USU Digital Commons*.

3.2 Additional Aerial Photo Collection

Additional aerial photos from 1939 were collected to complete the 1939 aerial photo coverage of the LDFK assembled by Jones (2018). Aerial photos from 1964/5, 1971, and 1984 were located and added to the analysis, allowing a better understanding of LDFK behavior following the 1952 and 1983/1984 floods. These photos were provided by the Utah Geological Survey (UGS) in Salt Lake City, Utah (Table 1.2). The newly collected aerial photos were mosaiced using AgiSoft Photoscan and georeferenced using ArcGIS Pro.

3.3 Topographic Analysis

Elevation information for LDFK was compiled from the October 3-6, 2017 LiDAR DEM. No air photos were taken with the LiDAR so channel boundaries for the LiDAR DEM were delineated from the September 2018 color air photos and checked against a hillshade of the 2017 DEM. The LDFK valley bottom was delineated and the average valley bottom width was calculated using the Utah State University Applied (USUAL) Watershed Tools (David et al., 2023). Channel banks were delineated on the 2018 air photo and the Planform Statistics Toolbox in ArcGIS (Lauer, 2006) was used to fit a channel centerline. After editing, the centroid of each abandoned surface was determined along the location of the nearest point on the 2017 channel centerline. The median elevation of each surface was determined using Zonal Statistics in ArcGIS Pro. The elevation of the surface relative to the modern channel was determined as the difference between the median elevation of the surface and the elevation of the 2017 channel centerline nearest to the centroid of the abandoned surface.

3.4 Field Work

Field observation of a subset of relict surfaces was conducted in July-August 2022 to determine surface grain size and to evaluate whether the abandoned surface had been modified by fluvial or human actions after being abandoned by the river. For each relict surface visited, we walked the boundary of the surface making notes regarding topography, texture, and vegetation. Where possible, a grain size sample was collected to gain an understanding of the riverbed texture of the original surface. Where the gravel bed material remains exposed on the bed surface, the surface layer of a 1-m by 1-m area was removed and sieved. Where a mantle of fine material had been deposited on top of river gravel, the fine sediment and organic material were removed from a 1-m by 1-m area and gravel was sampled to the lowest elevation of the largest exposed grain. Sieving was conducted in whole-phi fractions: > 64 mm, 32-64 mm, 16-32 m, 8-16 mm, and < 8 mm.

4. Results

This study focuses on how the LDFK responded to 87 years of very large flow augmentation. Superimposed on the trans-basin diversion flows were natural floods sufficiently large to exceed the magnitude of the diversion flows. In particular, two natural floods in 1952 and 1984 were at least three times the peak discharge of the augmented flow. The 1952 flood initiated extensive channel change that had not yet appeared in the first 36 years of flow diversion. The 1984 flood occurred 32 years later, such that the story of LDFK in the 20th century is one of the long-term channel changes over 87 years punctuated by disturbance and recovery from two major floods.

The evidence used to reconstruct the history of LDFK in the 20th century is based largely on its appearance in aerial photography and on the number, elevation, size, and configuration of surfaces abandoned by the river. The aerial photographs provide an indication of channel width and pattern (Jones, 2018) and the abandoned surfaces provide information on the elevation and texture of the river in the past.

This study relies heavily on visual interpretation of historical aerial imagery, therefore there is room for error and bias. The quantitative data collected in this study enhances and supports the visual interpretation of how the lower Diamond Fork River responded to changes in water and sediment supply throughout the 20th century.

4.1 Dry Canyon (Reach 1)

The LDFK in the 1.4 km Dry Canyon (DC) reach has a 1.5% slope (Table 1.1) and is largely confined between bedrock walls and further constrained by the Diamond Fork Forest Road (Figure 1.6). A largely single thread channel occupies this reach although in the early project period, there are locations where a broader braid plain occupied the entire valley bottom. The riverbed is coarse gravel/cobble with little storage of mobile sediment in the present regime. Figure 1.6 demonstrates how the elevation of the channel bed above the modern channel changed throughout history. Relict surfaces are colored based on the last year they were observed in the channel and confidence rating (CONF) describes how confident the mapping delineations were for each of these surfaces (5 is the highest confidence level).

The river in the early decades of the project period apparently aggraded by several meters. There are accounts in the US Bureau of Reclamation annual reports of road repair required in the first several years of the project operation. Although there is little accommodation space in this narrow valley, several relict surfaces that pre-date the 1939 air photos are preserved 2.5 m to 3.1 m above the modern channel (Figure 1.6) and were already forested in the first air

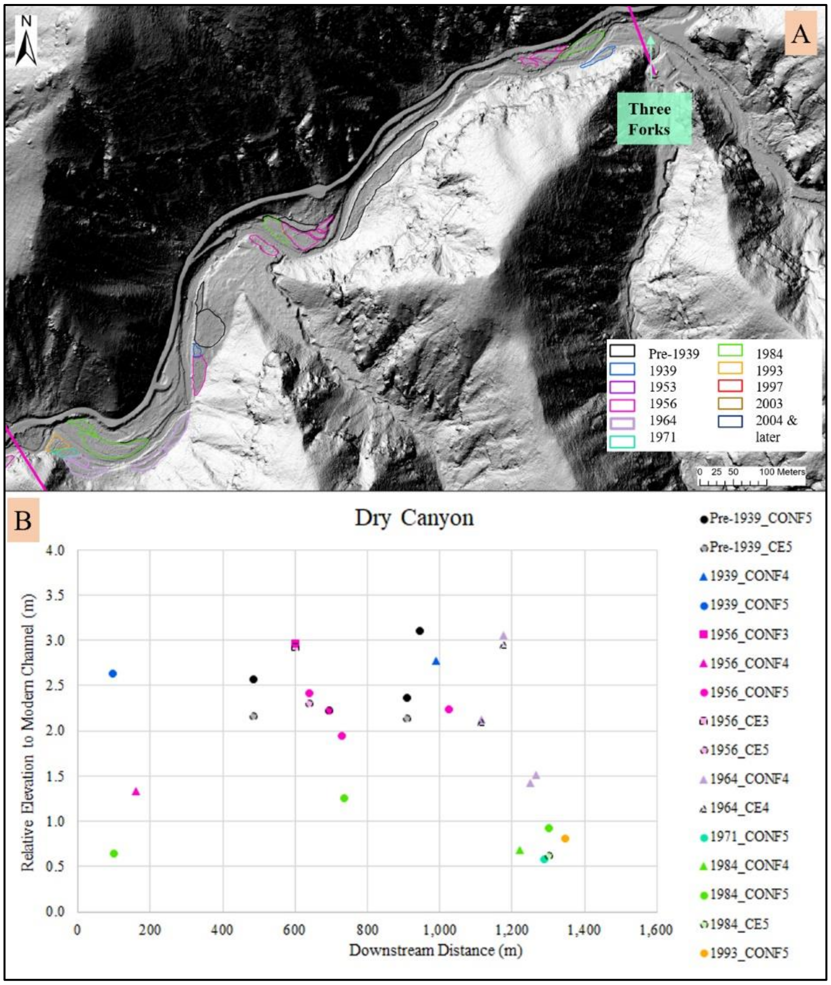

Figure. 1.6. Dry Canyon Reach: (A) DEM hillshade showing relict surfaces. (B) Relative elevation of relict surfaces with confidence mapping levels. CONF# = Mapping confidence level of surface. CE# = Corrected elevation of abandoned surface to account for thickness of fine mantle data collected in the field. Circle = Confidence Level 5, Triangle = Confidence Level 4, Square = Confidence Level 3. Although no 1939 surfaces were visited in this reach, it is estimated that the fine mantle thickness for these surfaces was around 0.2 m-0.3 m.

photos in 1939. The 1939 channel is wider and braided, filling the slightly wider valley bottom in the lower portion of the reach.

The 1952 flood appears to have established a dominant channel through this braid plain visible in the 1953 and 1956 photos. Vegetation established within parts of the former active channel by 1964 (Figure 1.7), which limited lateral channel movement after the 1952 flood. However, the widest portions remained a braided channel. Relict surfaces mapped within the active channel in 1953, 1956, and 1964 exceed 2.0 m above the modern channel (Figure 1.6). The

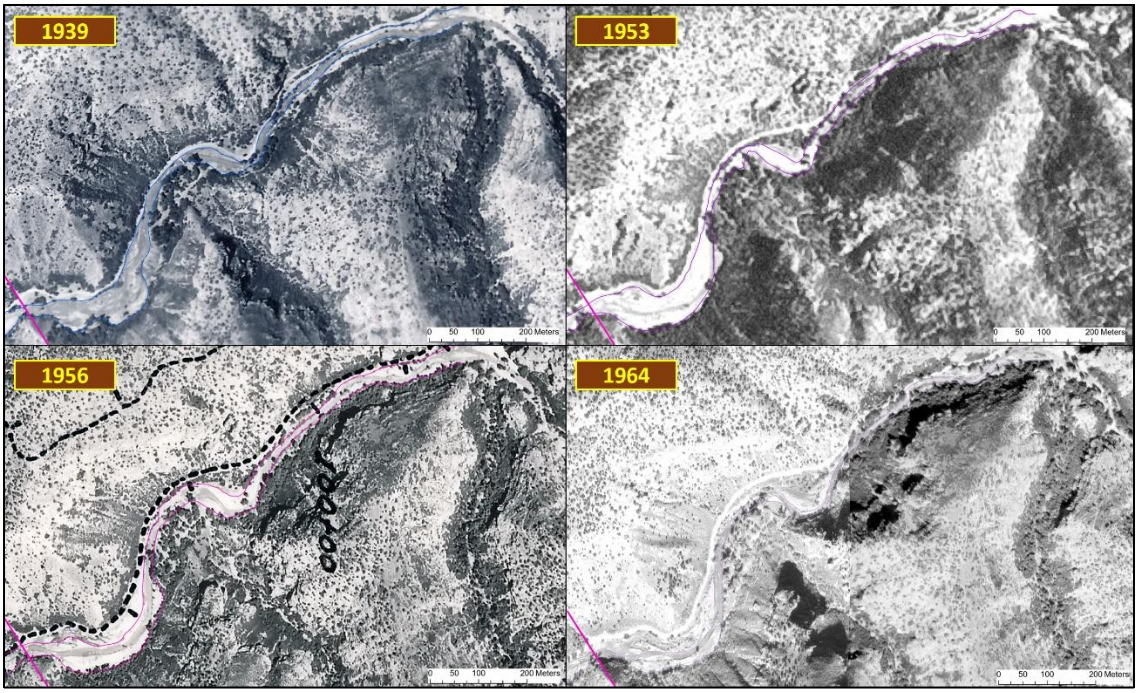

Figure 1.7. Air photos of DC Reach: 1939-1964. After the 1952 flood, the channel formed a single-thread channel through the broader braid plain and remained single thread throughout the reach. Lines depict active channel boundaries.

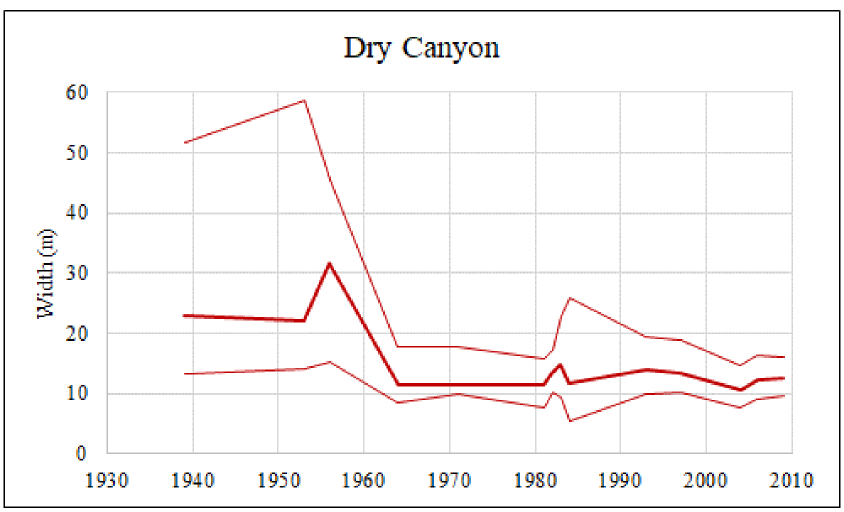

Figure 1.8. 10th percentile, median, and 90th percentile widths of Dry Canyon reach from 1939-2009. Increases in width in 1952 and 1984 were due to the two large natural floods during these years.

1956 median channel width was wider than the 1953 median channel width by 10 m whereas the 90th percentile width decreased by 13 m from 1953 to 1956, suggesting that the channel margin in some of the widest portions of the channel were being abandoned (Figure 1.8).

The relative elevation of the relict surfaces in this reach from 1939-1964 remained around 2.0 m – 2.5 m above the modern channel (Figure 1.6), indicating that the early period of rapid alluviation had ended and that the channel had achieved a transport steady state.

The floods of 1983 and 1984 removed vegetation along the wider portions of the valley bottom increasing the widest portions of the channel with a much smaller effect on the median width (Figure 1.8, Figure 1.9). Revegetation of these surfaces was mostly complete by 1993 and fully complete by 2003. Relict surfaces from 1984 are 0.5 to 1.0 m above the modern channel, which falls within the range of lateral topographic variation observed in this reach. The elevation of these surfaces, combined with the coarse grain size of riverbed material in this reach, suggests that there has been little river incision since the 1984 flood. Surfaces associated with the 1984 flood are roughly 1.5 m lower than surfaces associated with the 1952 flood (Figure 1.6), which are perhaps 0.5 m to 1.0 m lower than the highest observed surfaces created before 1939. This suggests that maximum channel aggradation, of at least 3.0 m, occurred prior to 1939, followed by downcutting in the 1952 flood and continued incision into the 1980s. In this reach, the channel has been narrowing since 1984 (Figure 1.8) while continuing to maintain single thread and meandering planform (Figure 1.9), further demonstrating that the channel cut down during this time.

The Dry Canyon reach is steep, coarse, and largely confined such that lateral channel change is strongly constrained. One braid plain developed in the early history of the diversion and was apparently replaced by a single thread channel by the 1952 flood. Subsequent floods likely covered the former braid plain, but multiple channels were reactivated, as shown in 1964. Channel dimensions in this reach are largely unchanged since the 1984 flood and did not change with the removal of the diversion flows in 2004. Vegetation establishment is slow on many

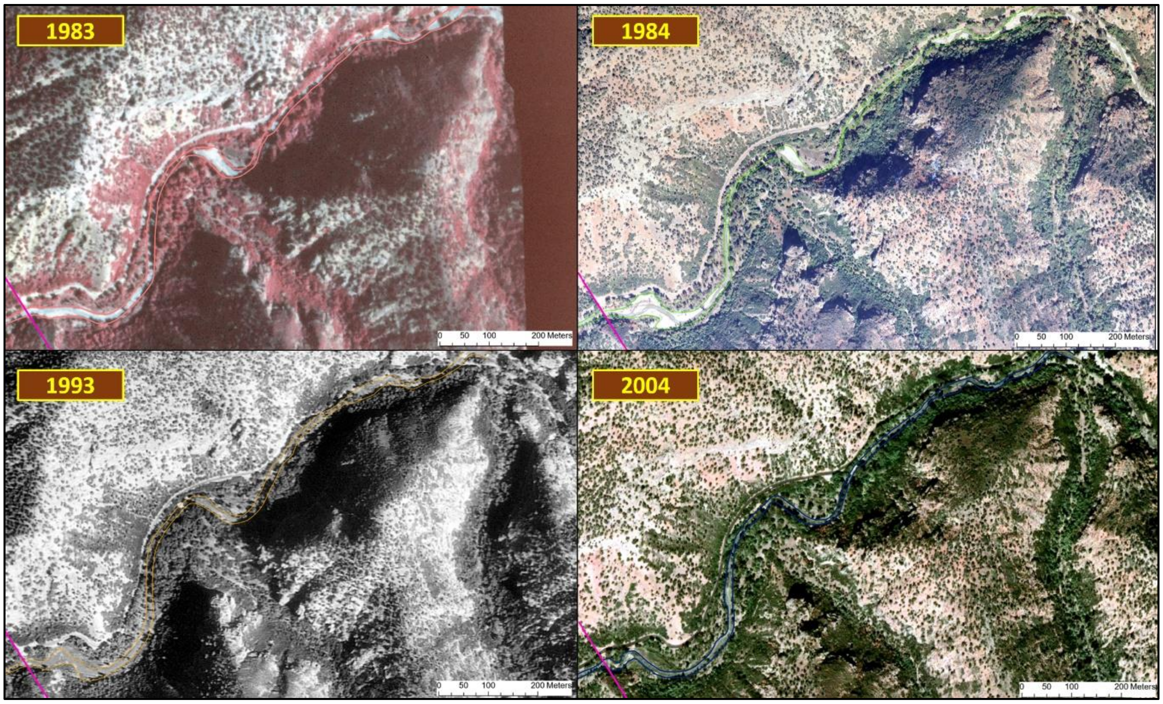

Figure 1.9. Air photos of DC Reach: 1983-2004. The floods of 1983 and 1984 removed some of the vegetation along the banks in this reach widening the median width of the active channel. Lines depict active channel boundaries.

channel-adjacent surfaces due to their very coarse grain size. Only one post-1984 surface was judged to be abandoned, and this was due to eventual establishment of vegetation.

4.2 Below Dry Canyon (Reach 2)

The LDFK in the 1.4 km Below Dry Canyon (BDC) reach has a 1.5% slope (Table 1.1), is largely confined between bedrock walls, and further constrained by the Diamond Fork Forest Road and bank protection adjacent to designated group campsites (Figure 1.10). The channel is largely single thread and slightly meandering. The riverbed is coarse gravel/cobble with little storage of mobile sediment in the present regime.

The river in the early decades of the project period aggraded at least several meters based on relict surfaces up to 4.0 m above the modern channel (Figure 1.10). Some of those surfaces were already forested by the first air photos in 1939. The 1939 channel was a single thread meandering channel with mature trees along the bank (Figure 1.11). After the 1952 flood, the

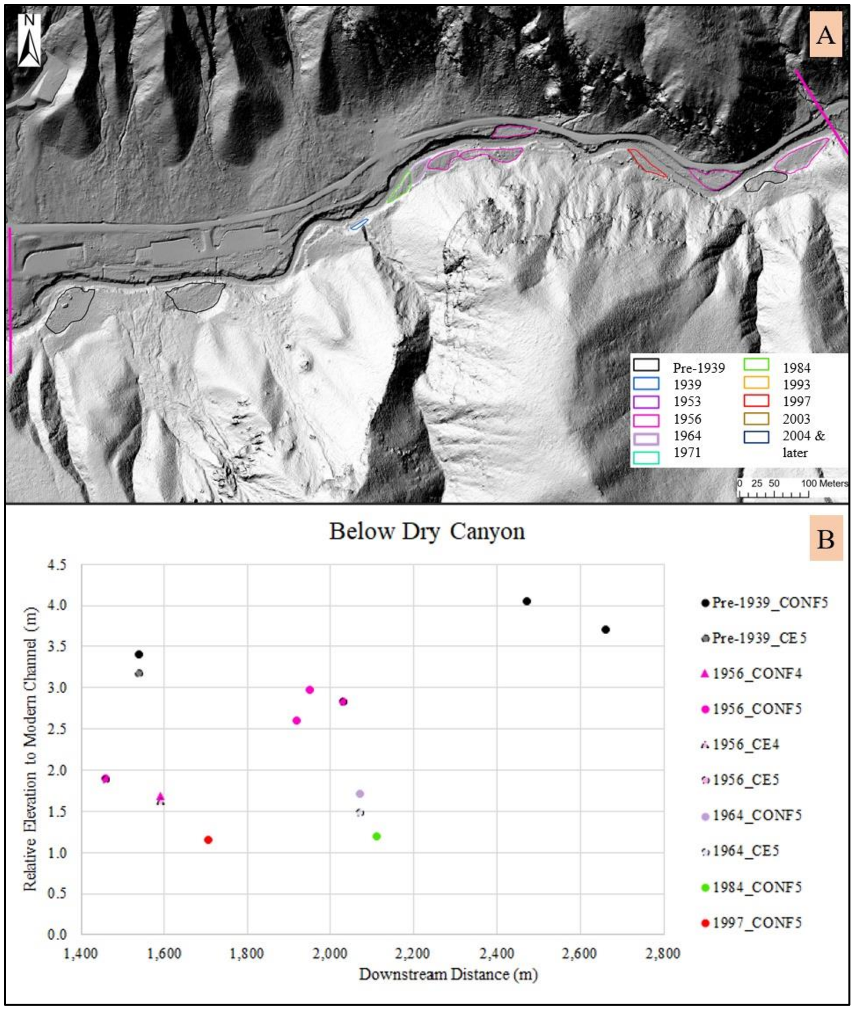

Figure. 1.10. Below Dry Canyon Reach: (A) DEM hillshade showing relict surfaces. (B) Relative elevation of relict surfaces with confidence mapping levels. CONF# = Mapping confidence level of surface. CE# = Corrected elevation of abandoned surface to account for thickness of fine mantle data collected in the field. Circle = Confidence Level 5, Triangle = Confidence Level 4.

channel appears to have cut down based on relict surfaces about a meter lower than relict surfaces formed before 1939 (Figure 1.10).

The 1952 flood widened the median channel width from 12 m in 1939 to 18 m in 1953 and the 90th percentile width increased from 22 m to 36 m in 1956 (Figure 1.12). A few mid-channel bars can be found throughout the channel in 1956 (Figure 1.11). The channel stayed a similar width until it narrowed by 7 m in 1964 and continued to narrow only slightly through the

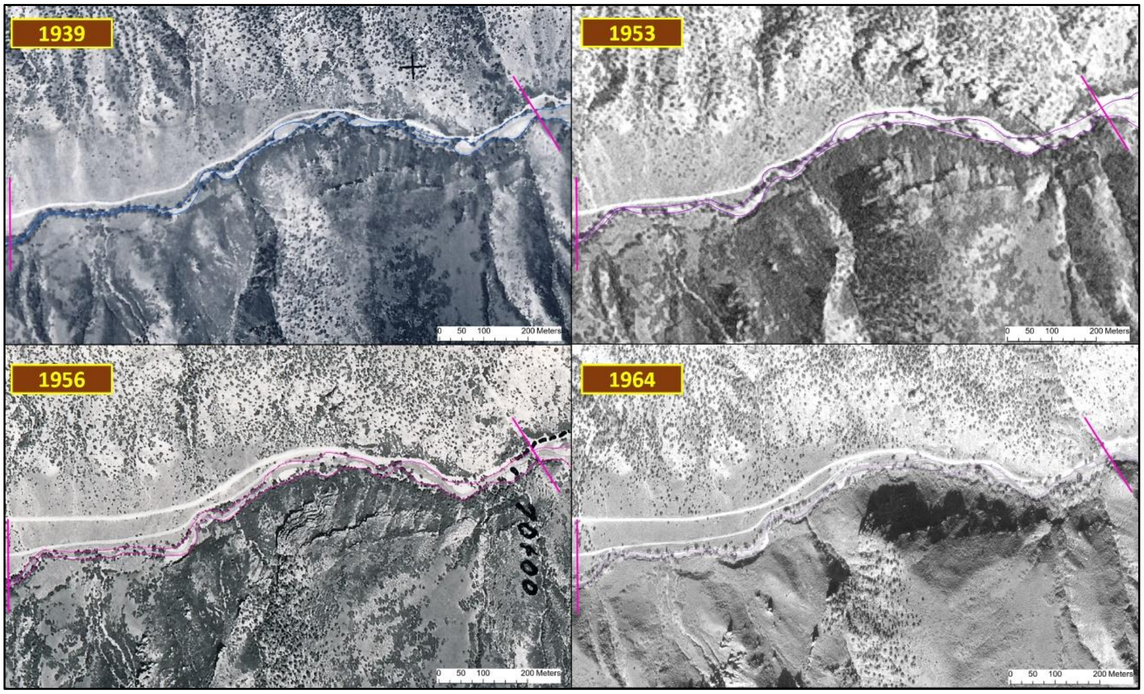

Figure 1.11. Air photos of BDC Reach: 1939-1964. The 1952 flood widened the median channel width, and a few sediment deposits can be found throughout the channel in 1956. Channel narrowing began in 1964. Lines depict active channel boundaries.

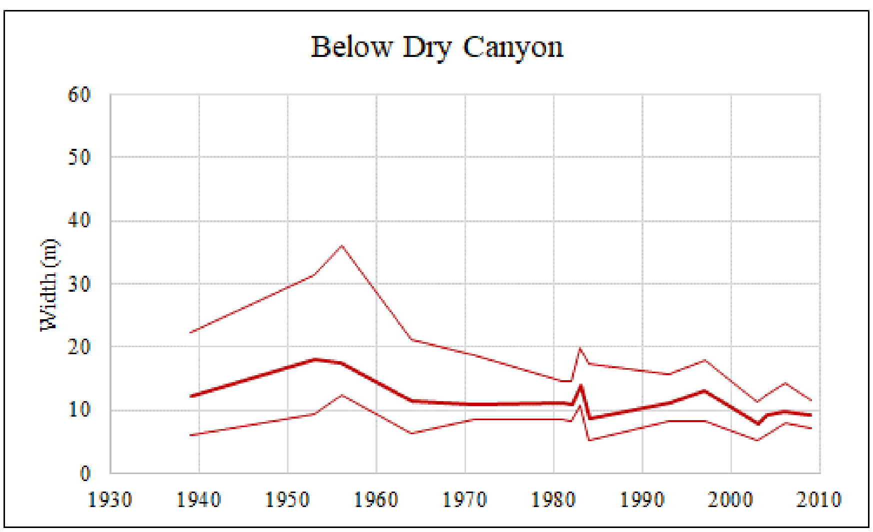

Figure 1.12. 10th percentile, median, and 90th percentile widths of Below Dry Canyon reach from 1939-2009. Increases in width in 1952 and 1984 were due to the two large natural floods during these years.

remainder of the study period (Figure 1.12). This narrowing was due to vegetation establishment along the banks which limited lateral channel movement after the 1952 flood.

The 1983/1984 floods had little impact on the channel width compared to the 1952 flood. However, these floods did remove some vegetation along the banks leaving behind gravel bars throughout the reach but had only a minor effect on channel width.

Only one relict surface remains from the 1984 channel and one from after 1984. These surfaces are within 1.2 m of the modern channel (Figure 1.10). Completion of Syar tunnel in 1996 and the removal of the diversion flows in 2004 did not significantly alter this reach of the LDFK channel.

4.3 Monks Hollow (Reach 3)

The LDFK in the 1.2 km Monks Hollow (MH) reach is less steep than the upstream reaches with a 1.1% slope (Table 1.1) and is largely confined by alluvial fans and confining bedrock. The reach is further constrained by the Diamond Fork Forest Road and bank protection adjacent to designated group campsites (Figure 1.13). The modern gage USGS 10149400 DIAMOND FORK ABV RED HOLLOW, NEAR THISTLE, UT is located immediately below the Monks Hollow Outlet in the downstream section of this reach. The channel is largely single thread and slightly meandering and the riverbed is coarse gravel/cobble with little storage of mobile sediment in the present regime.

The river in the early decades of the project period aggraded by at least 2.5 m based on the elevation of relict surfaces above the modern channel (Figure 1.13). The first air photo demonstrates that some of those surfaces were forested by 1939. The channel in 1939 was a single thread meandering channel with dense mature trees along the banks (Figure 1.14).

The 1952 flood did not change the median channel width between 1939 and 1953 although the 90th percentile width increased by more than 10 m (Figure 1.15). The 1953 channel started high and cut down what appears to be mid-way through the Monks Hollow reach, around

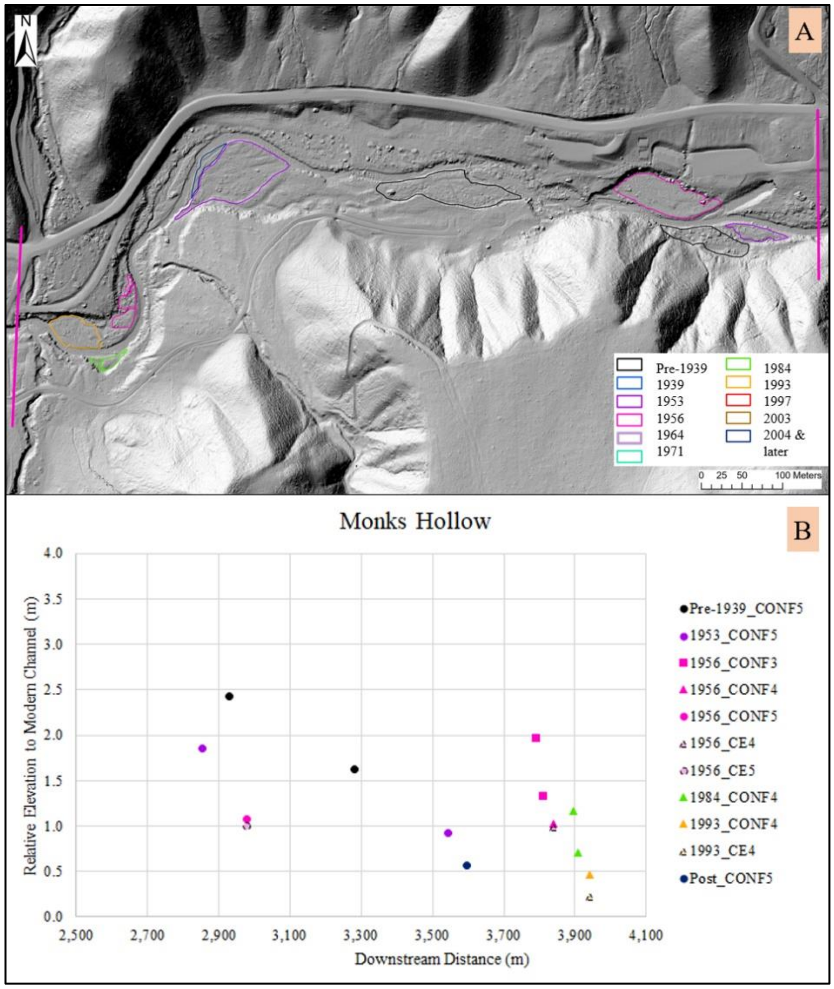

Figure 1.13. Monks Hollow Reach: (A) DEM hillshade showing relict surfaces. (B) Relative elevation of relict surfaces with confidence mapping levels. CONF# = Mapping confidence level of surface. CE# = Corrected elevation of abandoned surface to account for thickness of fine mantle data collected in the field. Circle = Confidence Level 5, Triangle = Confidence Level 4.

river meter (RM) 3,500, based on one abandoned surface cut by the 1953 channel that was almost 2.0 m above the modern channel while the other relict surface, located downstream of the first surface, was only 1.0 m above the modern channel (Figure 1.13). The 1952 flood deposited sediment along the banks leaving behind gravel bars and widening the active channel.

Between 1956 and 1964, the channel began to narrow with the widest sections of the channel decreasing in width by a factor of two (Figure 1.15). This narrowing was due to vegetation establishment along the banks which restricted lateral channel movement after the

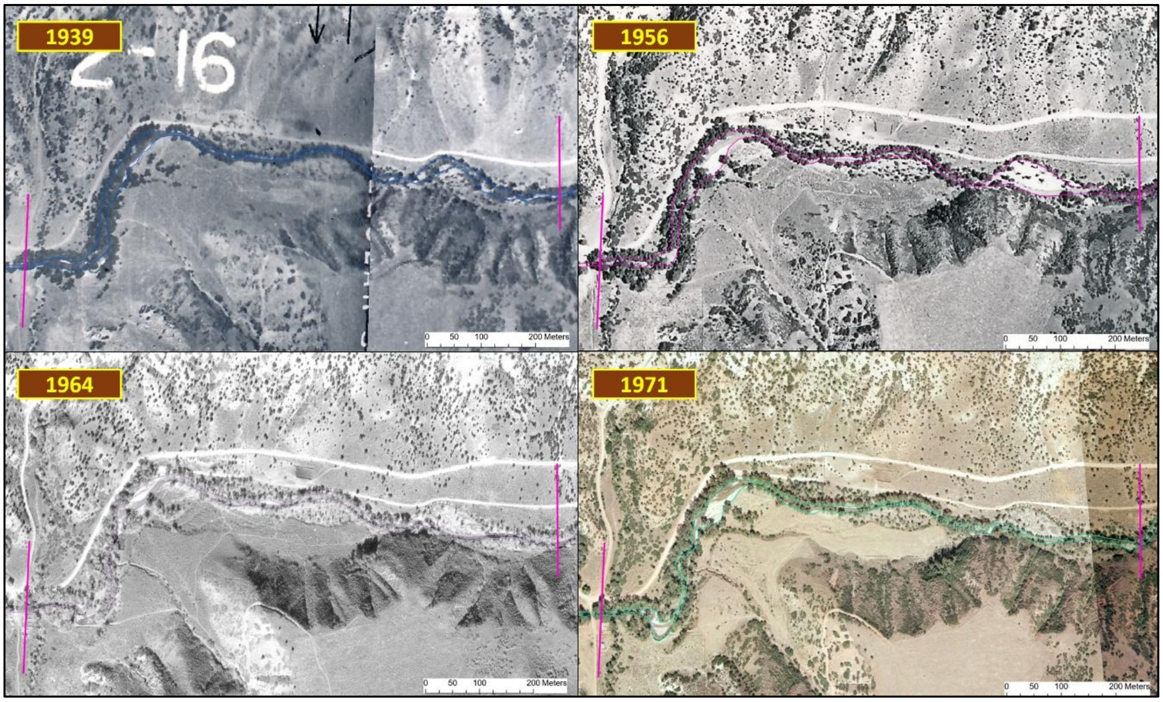

Figure 1.14. Air photos of MH Reach: 1939-1971. The 1952 flood widened roughly 10% of the wider section of the channel give that the median channel width did not change between 1939 and 1953. Lines depict active channel boundaries.

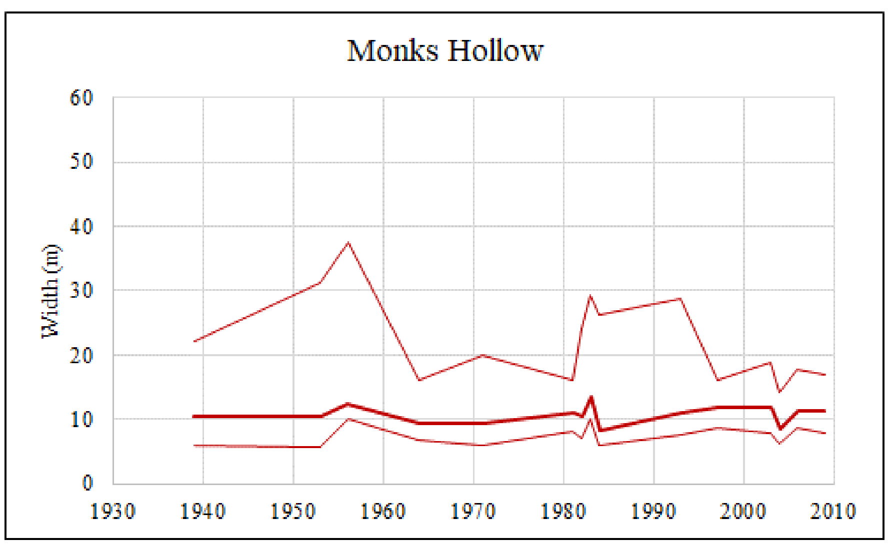

Figure 1.15. 10th percentile, median, and 90th percentile widths of Monks Hollow reach from 1939-2009. Increases in width in 1952 and 1984 were due to the two large natural floods during these years.

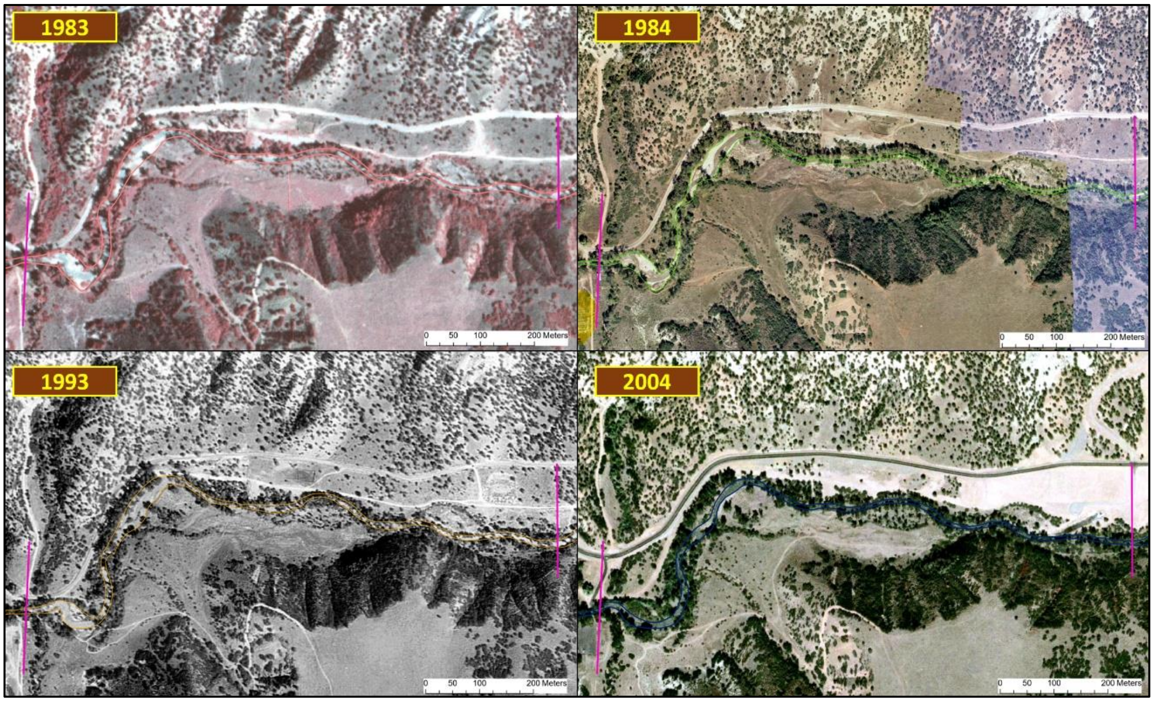

Figure 1.16. Air photos of MH Reach: 1983-2004. The 1983 flood had a slightly greater impact on the channel compared to the 1984 flood. Lines depict active channel boundaries.

1952 flood. About 10% of the channel was braided on the downstream end of this reach from 1964-1971 (Figure 1.14) and by 1981, the channel was single thread once again.

The 1983 and 1984 floods removed vegetation (Figure 1.16) such that the widest portions of the channel increased in width by about 10 m (Figure 1.15). Vegetation that did not recover by 1984, was able to reestablish by 1997.

The 1993 channel was also quite wide with the widest portions of the channel widening by almost 2.5 m with those sections narrowing by 1997 (Figure 1.15). The width of the channel has changed very little since 1997 and overall, the channel has followed a similar planform throughout history. This was most likely due to the confinement of the valley setting.

4.4 Below Monks Hollow (Reach 4)

The LDFK in the 0.95 km Below Monks Hollow (BMH) reach has a 1.3% slope (Table 1.1), is largely confined by alluvial fans and confining bedrock. This reach is further constrained

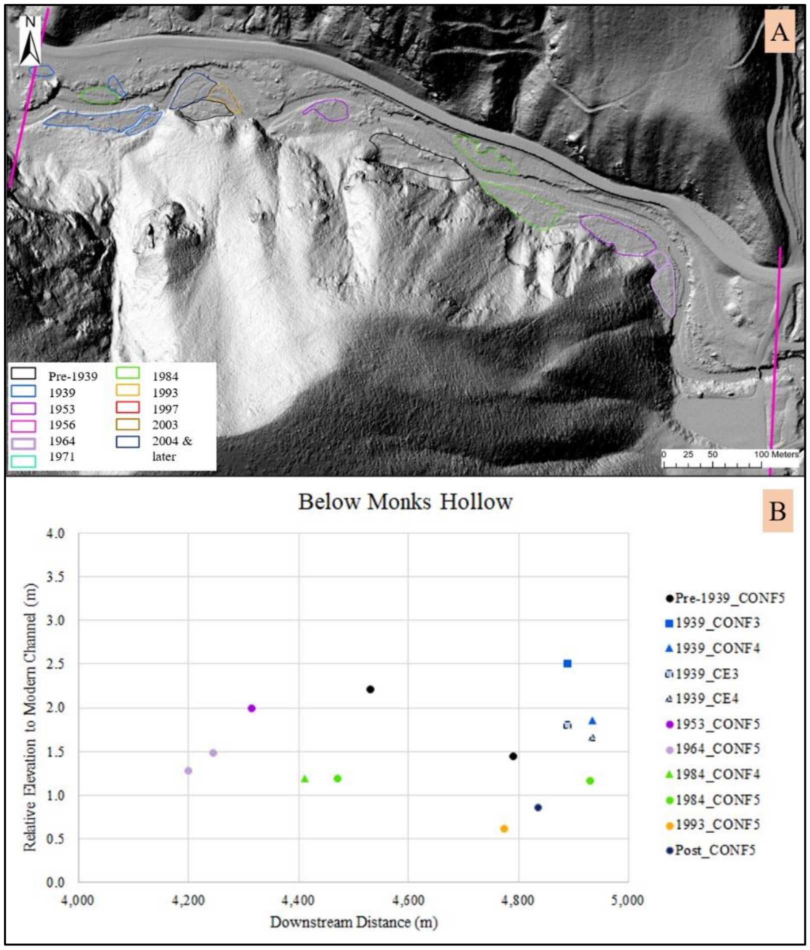

Figure 1.17. Below Monks Hollow Reach: (A) DEM hillshade showing relict surfaces. (B) Relative elevation of relict surfaces with confidence mapping levels. CONF# = Mapping confidence level of surface. CE# = Corrected elevation of abandoned surface to account for thickness of fine mantle data collected in the field. Circle = Confidence Level 5, Triangle = Confidence Level 4, Square = Confidence Level 3.

by the Forest Road (Figure 1.17) and the channel is largely single thread and slightly meandering. The riverbed is coarse gravel/cobble with little storage of mobile sediment in the present regime.

The river in the early decades of the project period aggraded based on relict surfaces up to 2.0 m above the modern channel (Figure 1.17). Some of these surfaces were already forested in the first air photos in 1939. The 1939 channel was single thread and meandering with mature vegetation along the banks (Figure 1.18). This channel and the pre-1939 channel were of similar elevations demonstrated by the relict surfaces during those years that were of similar relative elevations to the modern channel (Figure 1.17).

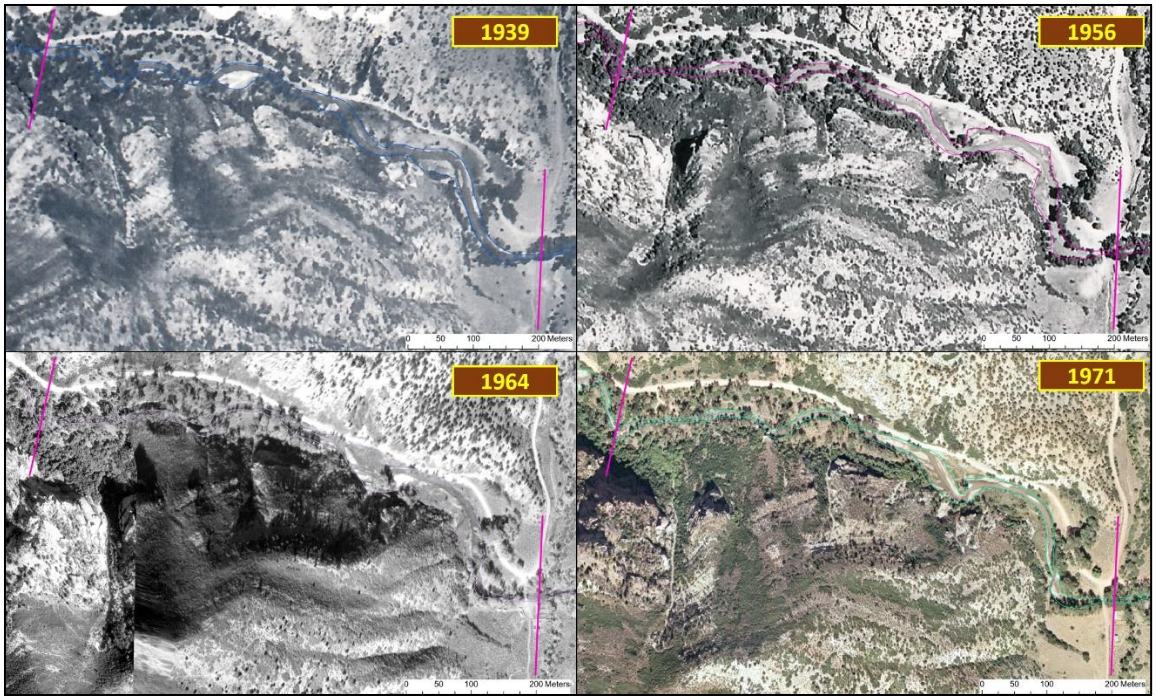

Figure 1.18. Air photos of BMH Reach: 1939-1971. The 1952 flood caused the channel to widen, however only in about 10% of the channel given that the median channel width decreased by 3 m. Lines depict active channel boundaries.

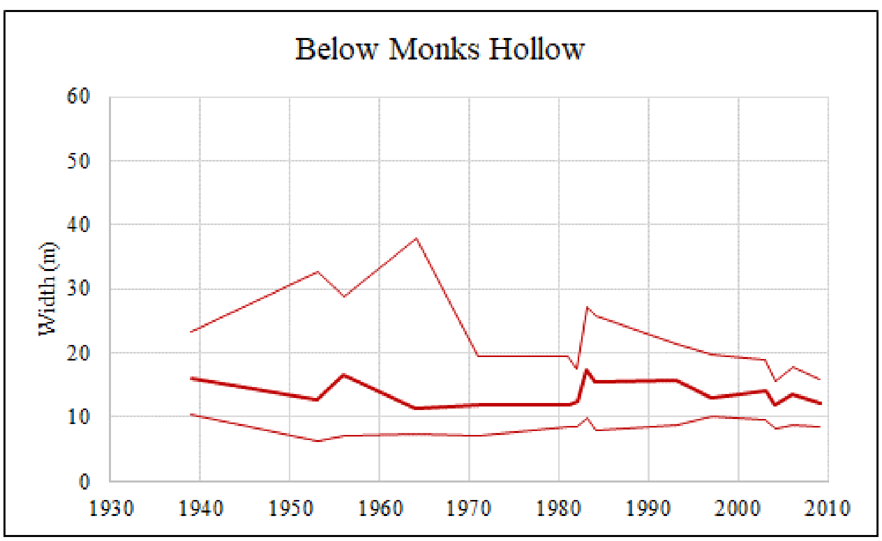

Figure 1.19. 10th percentile, median, and 90th percentile widths of Below Monks Hollow reach from 1939-2009. Increases in width in 1952 and 1984 were due to the two large natural floods during these years.

The 1952 flood caused the widest sections of the channel to widen further, although the median channel width decreased by 3.0 m (Figure 1.19). The channel shifted and gravel bars were deposited in the wider sections of the channel which caused an increase in the active channel width. One relict surface remains from 1953 at 2.0 m above the modern channel, which is similar in elevation to those left by the 1939 channel (Figure 1.17).

Between 1964 and 1971, the channel began to narrow with the widest sections of the channel narrowing by 19 m (Figure 1.19). This narrowing was due to vegetation establishment along the banks which restricted lateral channel movement after the 1952 flood. Also, from 1964 and 1971, channel length increased by 40 m because of growth of meander bends in the upstream section of this reach (Figure 1.18). This bend was then straightened by the 1984 flood (Figure 1.20). This straightening shortened the channel back to its length in 1964.

The 1984 flood eliminated some of the vegetation around the channel, again widening the wider sections of the channel (Figure 1.19). A small bend cut off occurred in the upstream portion of the reach (Figure 1.20). This flood caused the channel to cut down slightly and left it just over 1.0 m above the modern channel (Figure 1.17).

In 1997, two meander bends sharpened in the downstream section of this reach, lengthening the channel by 20 m. The channel has stayed a similar length since then. After the removal of the diversion flows in 2004, some narrowing occurred, but overall, very little has changed in this reach. There was only one post-project relict surface, meaning a fluvial surface formed after 2003, further demonstrating that not much has changed in the channel since the removal of the diversion flows in 2004.

4.5 Red Ledges (Reach 5)

The LDFK in the 2.0 km Red Ledges (RL) reach has a 1.0% slope (Table 2.1), is largely confined by alluvial fans and confining bedrock. This reach is further constrained by the Diamond Fork Forest Road (Figure 1.21) with the channel largely single thread and slightly

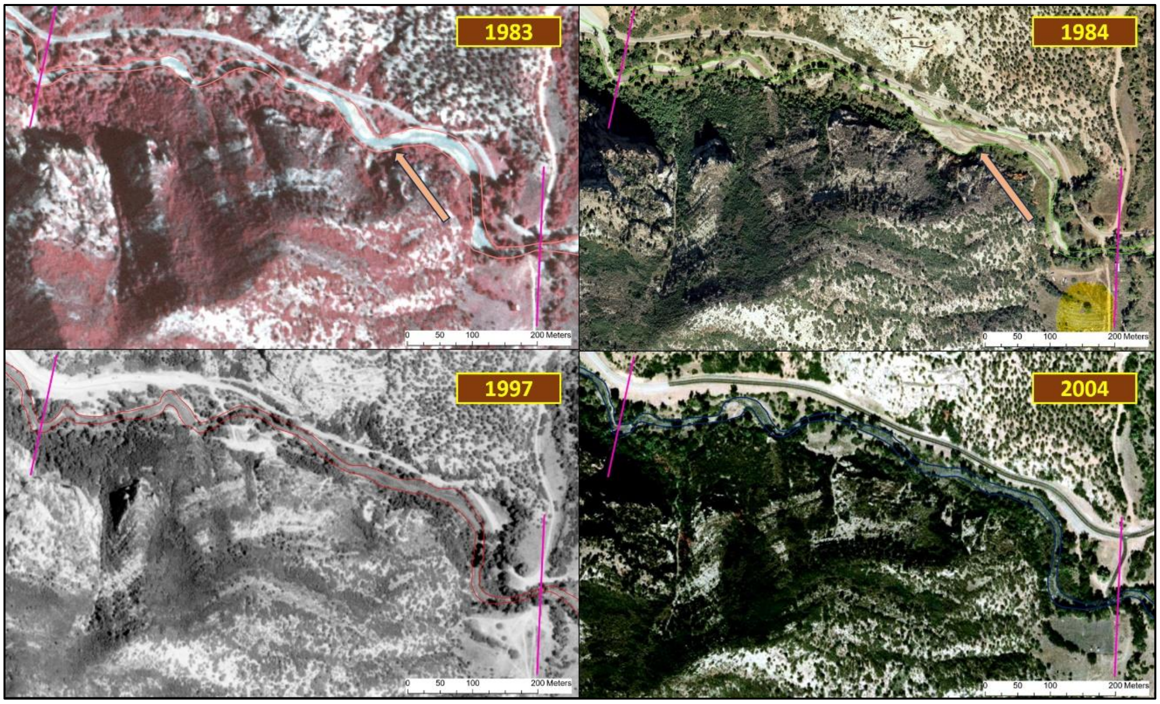

Figure 1.20. Air photos of BMH Reach: 1983-2004. The arrow points to a small bend cut off that occurred due to the 1984 flood. Lines depict active channel boundaries.

meandering. The historic gage USGS 10149500 DIAMOND FORK BELOW RED HOLLOW, NEAR THISTLE, UT is located in the middle of this reach. The riverbed is gravel and cobble with little storage of mobile sediment in the present regime.

The river in the early decades of the project period aggraded based on relict surfaces more than 2.0 m above the modern channel (Figure 1.21). Some of those surfaces were already forested in the first air photos in 1939. The 1939 channel was a single thread meandering channel with vegetation along the banks (Figure 1.22) and at a similar elevation as the previous channel at 2.0 m above the modern channel (Figure 1.21).

The 1952 flood caused the channel to widen from a median width of 14 m in 1939 to a median width of 21 m in 1953 (Figure 1.23), causing some gravel bar deposits along the banks (Figure 1.22), which widened the active channel. These gravel bar deposits occurred mainly in the wider sections of the channel, increasing the width by almost 20 m in these sections (Figure1.23). Vegetation established on these gravel bar deposits which restricted further lateral

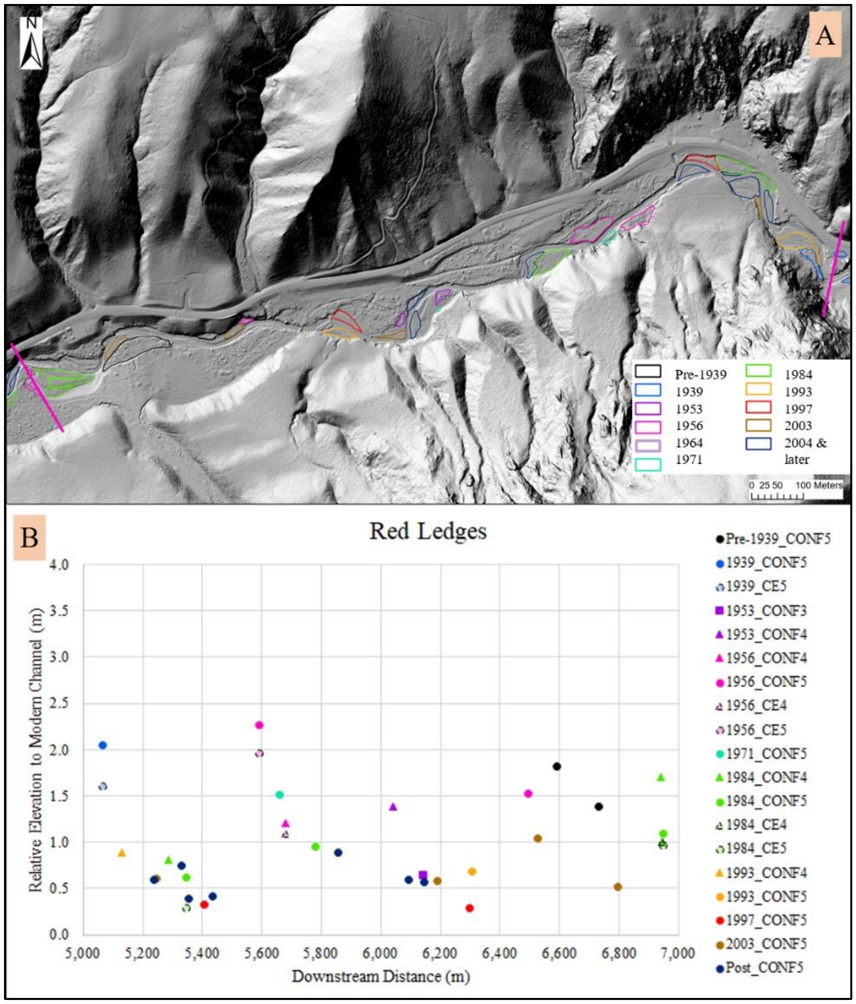

Figure 1.21. Red Ledges Reach: (A) DEM hillshade showing relict surfaces. (B) Relative elevation of relict surfaces with confidence mapping levels. CONF# = Mapping confidence level of surface. CE# = Corrected elevation of abandoned surface to account for thickness of fine mantle data collected in the field. Circle = Confidence Level 5, Triangle = Confidence Level 4, Square = Confidence Level 3.

channel movement after the 1952 flood. Channel planform followed a similar pattern from 1939-1956, even with the channel widening due to the 1952 flood. The elevation of the 1956 relict surfaces was similar compared to the 1939 relict surfaces (Figure 1.21). Between 1953 and 1956 the channel sharpened a few of the meander bends increasing overall channel length by 80 m and then further by 60 m in 1964. By 1971 the channel began to shorten again as a few of these meander bends were slightly straightened by the channel.

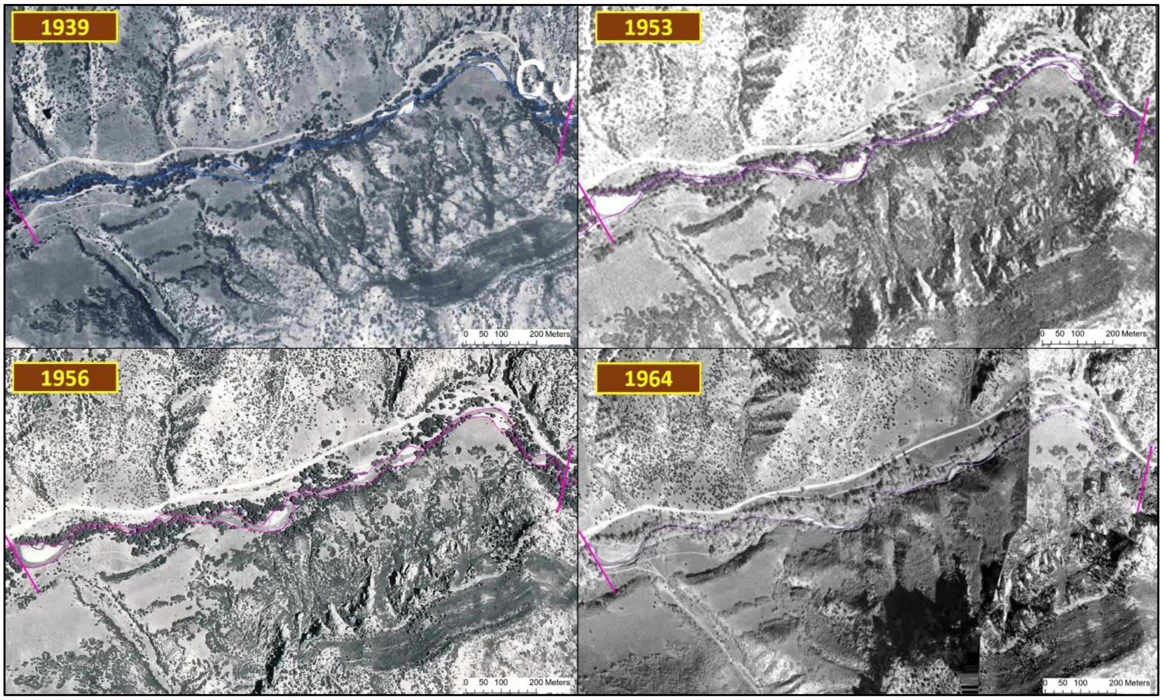

Figure 1.22. Air photos of RL Reach: 1939-1964. The 1952 flood widened the channel eliminating some of the vegetation along the banks. Lines depict active channel boundaries.

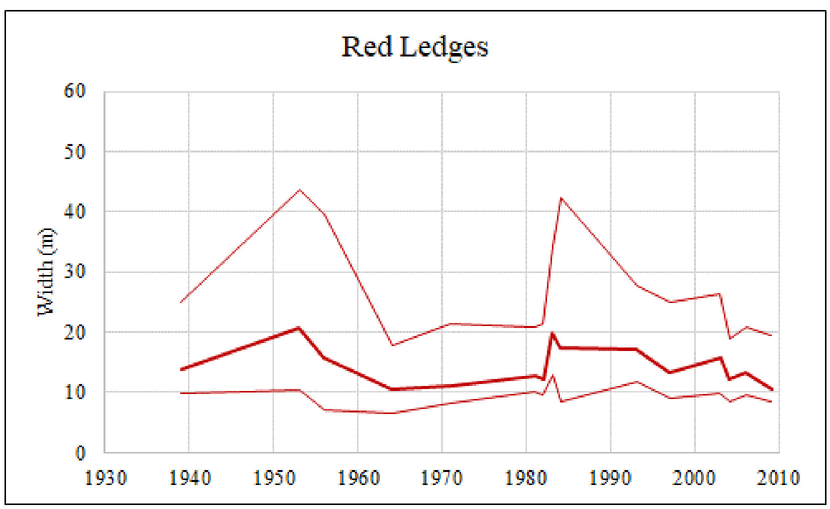

Figure 1.23. 10th percentile, median, and 90th percentile widths of Red Ledges reach from 1939-2009. Increases in width in 1952 and 1984 were due to the two large natural floods during these years.

The median channel width narrowed 8.5 m from 1953-1982 with the 90th percentile width drastically decreasing by 21.5 m from 1956 to 1964 (Figure 1.23). The 1983 and 1984 floods eliminated vegetation on the banks and widened the median channel width to 20 m in 1983 with this median width decreasing slightly to 17 m in 1984 (Figure 1.23). The wider sections of the channel increased the most in width during these floods. These sections increased by 13 m in 1983 and then another 8 m in 1984 (Figure 1.23). Both floods eliminated vegetation on the banks with much of the vegetation recovering by 1993 (Figure 1.24).

Quite a few fluvial surfaces formed in this reach after 2003, indicating that the channel has remained active since the removal of the diversion flows in 2004. Most of these post-project relict surfaces are point bars left behind by growing and shifting meander bends. Overall, the channel planform in this reach has followed a similar pattern throughout history. There was not a strong pattern in the relative elevation of relict surfaces above the modern channel suggesting that the LDFK channel has stayed at similar elevations throughout history (Figure 1.21).

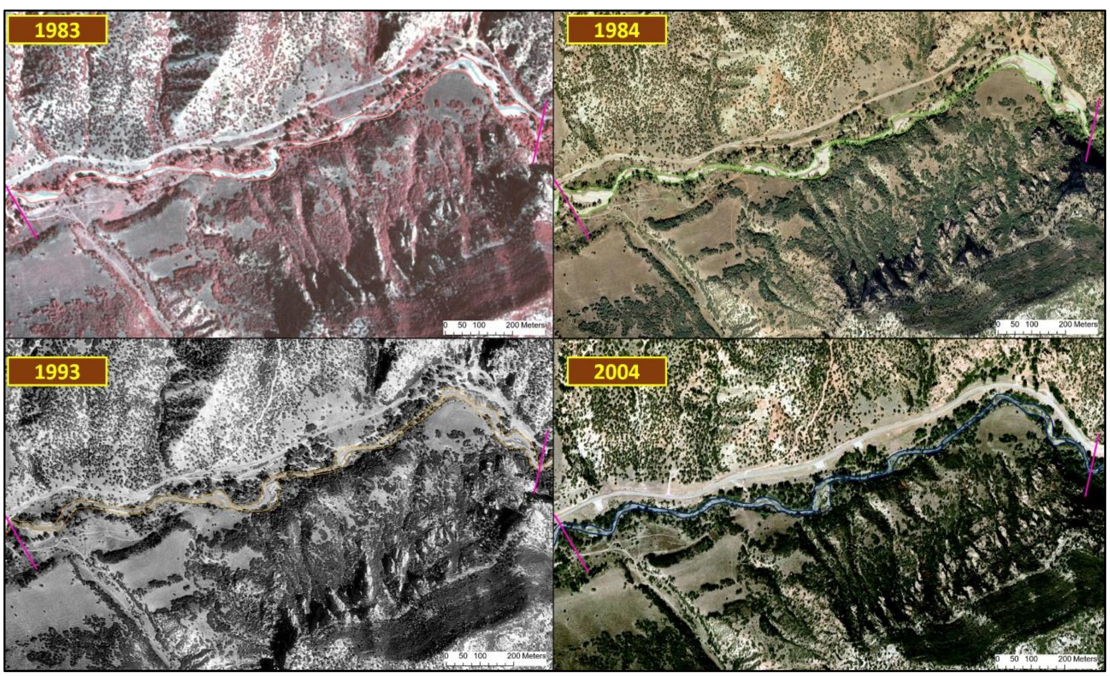

Figure 1.24. Air photos of RL Reach: 1983-2004. The 1983 and 1984 floods widened the median channel width, and the channel has stayed a similar planform since 1993. Lines depict active channel boundaries.

4.6 Diamond Campground (Reach 6)

The LDFK in the 3.1 km Diamond Campground (DCG) reach is the longest reach and contains the largest designated campground on the river operated by the US Forest Service. This reach has a 0.9% slope (Table 1.1) and is largely unconfined but constrained by the Diamond Fork Forest Road and a terrace hillslope (Figure 1.25). The channel is predominantly single thread with localized braided sections at some points in the past. The riverbed is coarse gravel with some mobile sediment in the present regime.

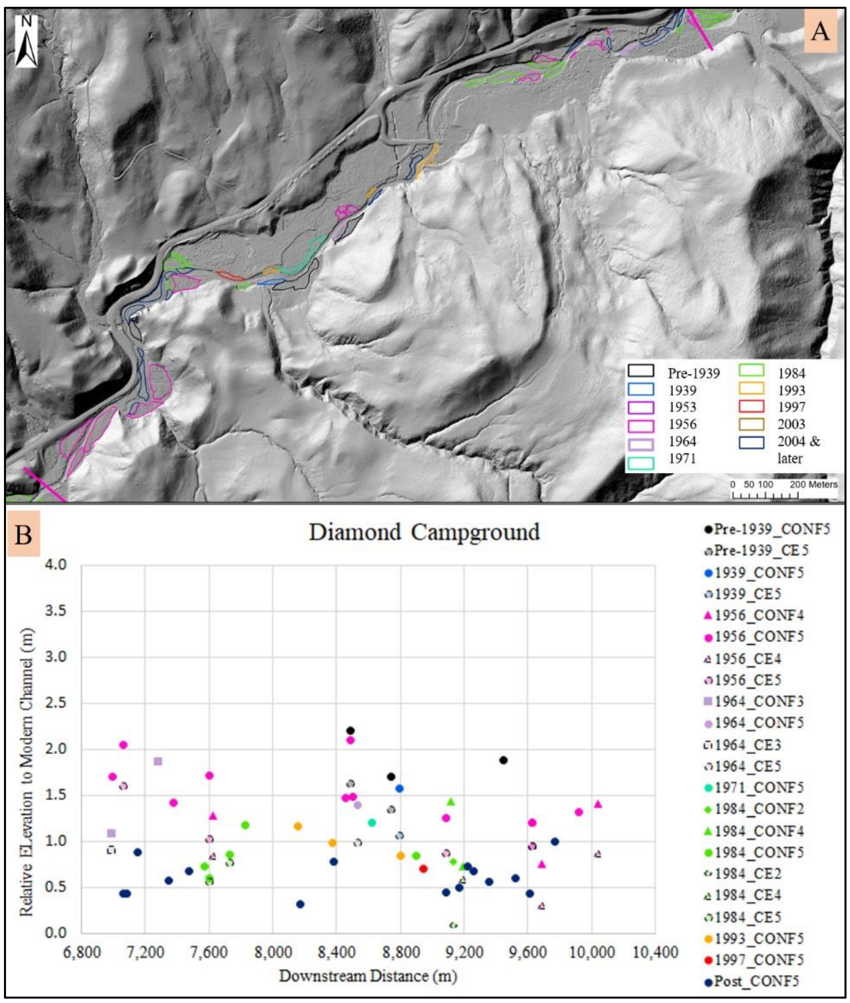

Figure 1.25. Diamond Campground Reach: (A) DEM hillshade showing relict surfaces. (B) Relative elevation of relict surfaces with confidence mapping levels. CONF# = Mapping confidence level of surface. CE# = Corrected elevation of abandoned surface to account for thickness of fine mantle data collected in the field. Circle = Confidence Level 5, Triangle = Confidence Level 4, Square = Confidence Level 3.

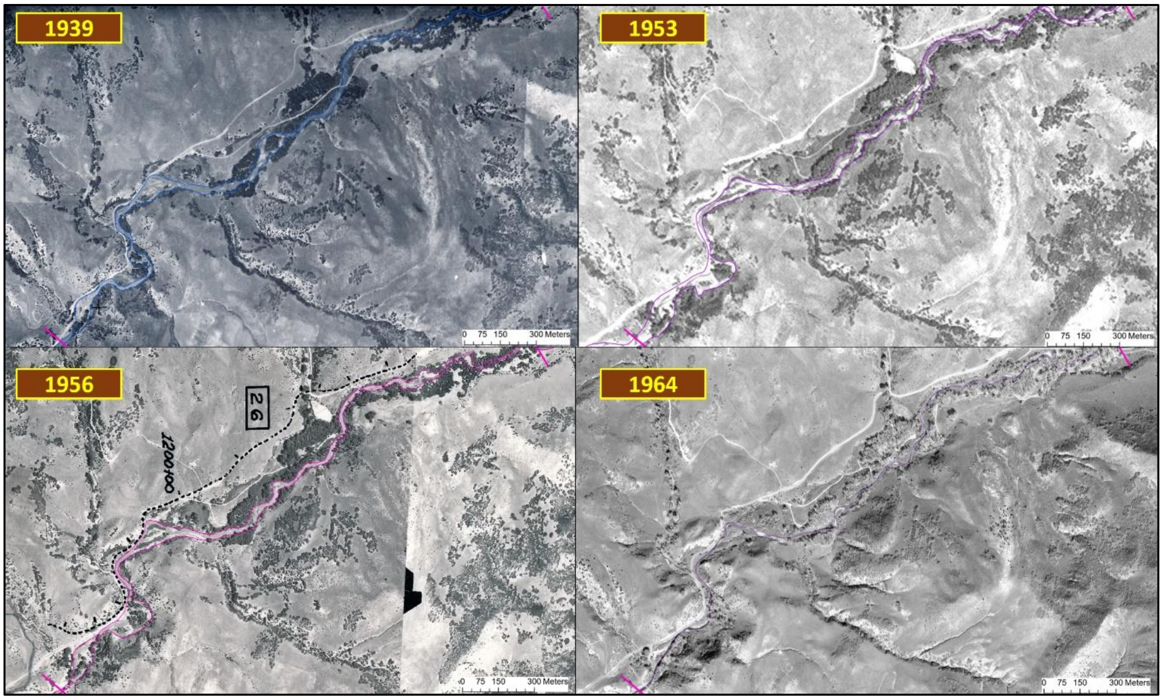

Figure 1.26. Air photos of DCG Reach:1939-1964. The 1952 flood caused the active channel to widen from 1939 to 1956. Lines depict active channel boundaries.

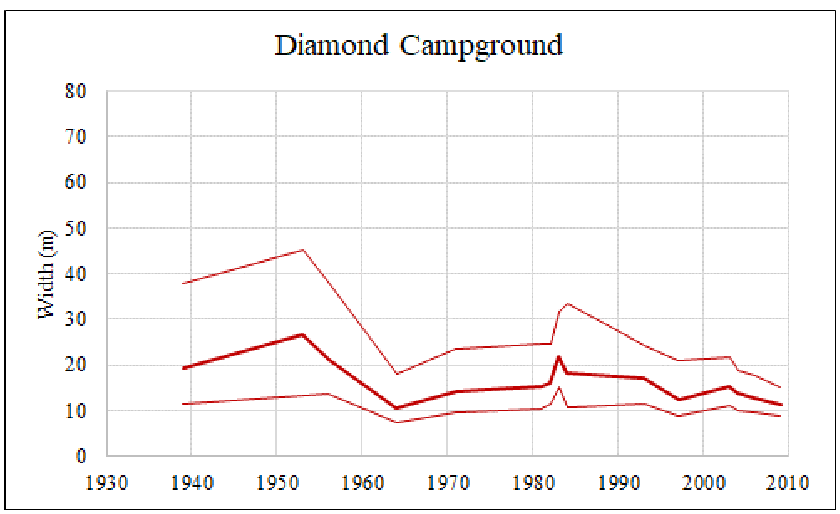

Figure 1.27. 10th percentile, median, and 90th percentile widths of Diamond Campground reach from 1939-2009. Increases in width in 1952 and 1984 were due to the two large natural floods during these years.

The river in the early decades of the project period aggraded, based on relict surfaces up to 2.0 m above the modern channel (Figure 1.25). Some of those surfaces were already forested by the first air photos in 1939. The 1939 channel was a meandering single thread channel with several braided reaches that were about 10% of the channel length (Figure 1.26).

The 1952 flood caused the median channel width to widen from 19 m in 1939 to 26.5 m in 1956 with sediment deposits found throughout the channel (Figure 1.26, Figure 1.27). In the downstream section of this reach, braided sections became vegetated producing split flow around an island.

By 1964, the channel cut off five bends leaving the channel straighter and the 1956 relict surfaces with an average of 1.5 m above the modern channel (Figure 1.25, Figure 1.26). Growth of other meander bends compensated for bend cutoffs and the overall channel lengthened by 60 m since 1956. The channel narrowed over this period with the median channel width decreasing by 11 m and the wider sections of the channel narrowing by 20 m (Figure 1.27).

The 1971 and 1980s channels followed a similar planform to the 1964 channel until the 1984 flood. High flows in 1983 and 1984 produced some channel shifting and an increase in width of the wider sections (Figure 1.27). About 10% of the channel in this reach was braided during this time with the flood removing vegetation mainly in the upstream portion of the reach and leaving behind numerous bare surfaces/gravel bars next to the channel throughout the entirety of the reach (Figure 1.28).

By 1993, the channel began to narrow (Figure 1.27) and became a meandering single thread channel (Figure 1.28). The channel in the Diamond Campground reach has remained single thread throughout the reach ever since. The channel planform has stayed the same since the completion of Syar tunnel in 1996 and the removal of the diversion flows in 2004. Bend growth and lateral channel shifting have continued since the removal of the diversion flows, leaving low elevation relict surfaces (less than 1 m above the modern channel; Figure 1.25).

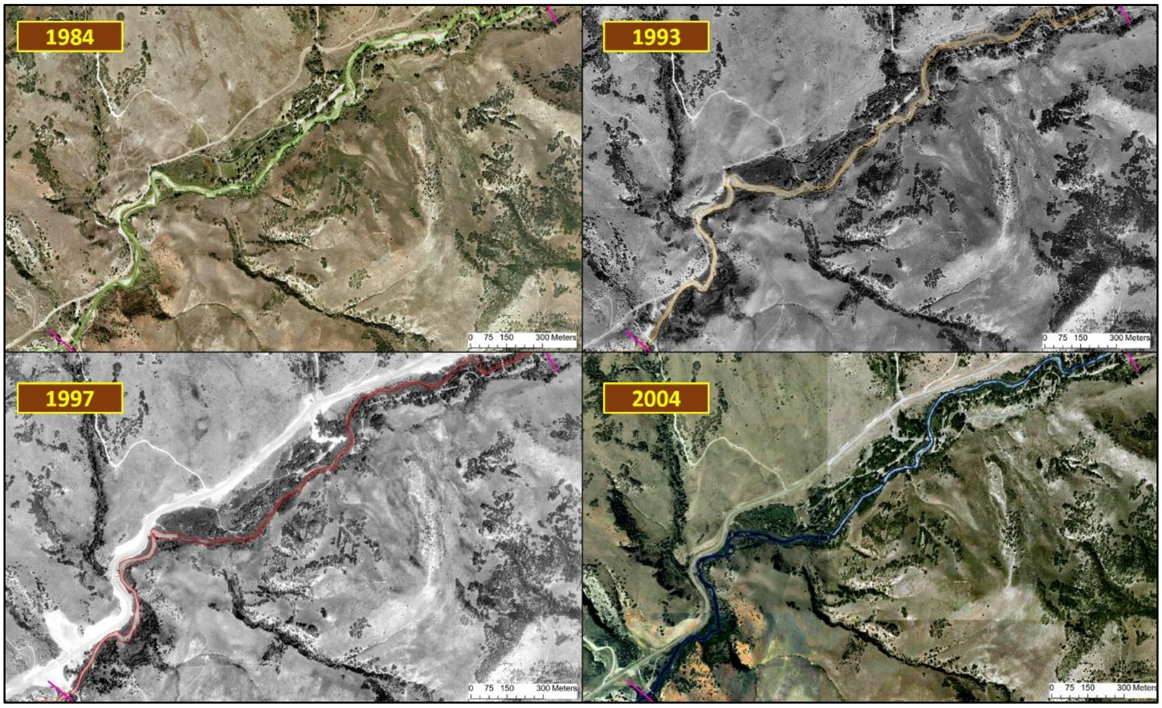

Figure 1.28. Air photos of DCG Reach: 1984-2004. The 1984 flood widened the active channel and by 1993, the channel was single thread, and the channel pattern has stayed the same ever since. Lines depict active channel boundaries.

4.7 Below Brimhall Bridge (Reach 7)

The LDFK in the 2.0 km Below Brimhall Bridge (BBH) reach has a 0.7% slope (Table 1.1) and is mostly unconfined (Figure 1.29). Brimhall Bridge is located near the upstream boundary of the reach and is the location of the historic gage USGS 10150000 DIAMOND FORK NEAR THISTLE, UTAH. The channel is largely single thread in this reach although there have been sections of braiding in the past. The riverbed is coarse gravel with some mobile sediment in the present regime.

The channel in 1939 was primarily a single thread meandering channel with about 20% of the channel braided in the downstream section of the reach. Mature trees can be found along the banks (Figure 1.30). The 1952 flood significantly widened the active channel from a median width of 19 m in 1939 to 38 m in 1953 and deposited gravel bars inside the channel (Figure 1.30, Figure 1.31). The wider sections of the channel also increased in width by 20 m (Figure 1.31). An

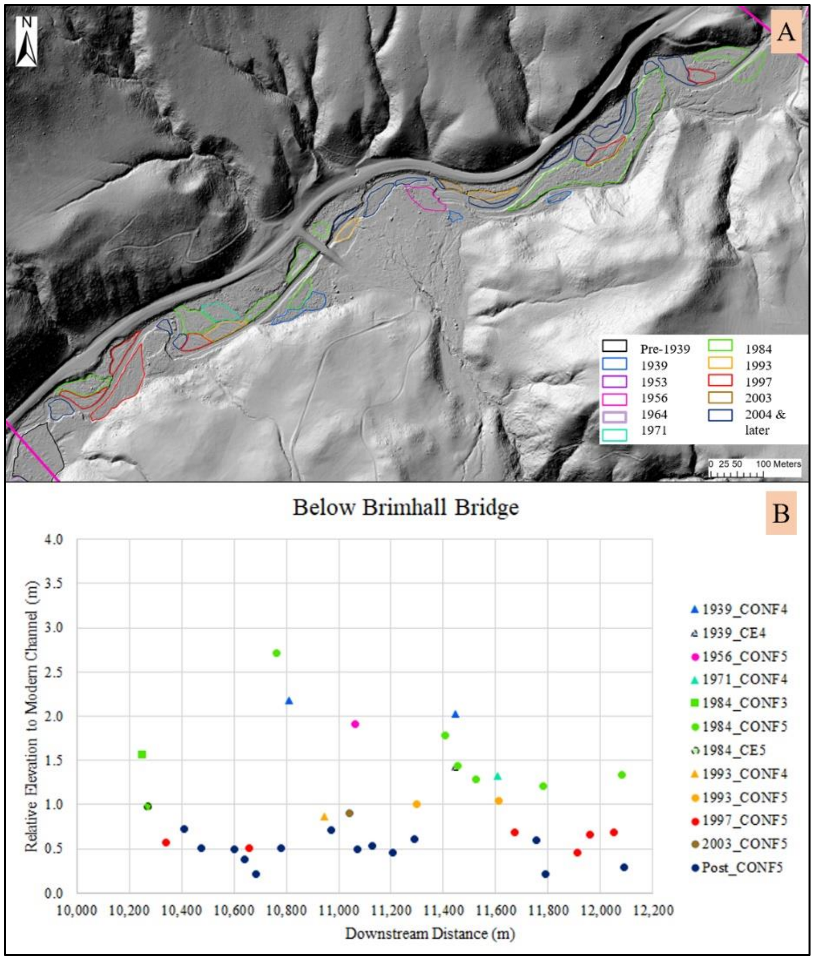

Figure 1.29. Below Brimhall Reach: (A) DEM hillshade showing relict surfaces. (B) Relative elevation of relict surfaces with confidence mapping levels. CONF# = Mapping confidence level of surface. CE# = Corrected elevation of abandoned surface to account for thickness of fine mantle data collected in the field. Circle = Confidence Level 5, Triangle = Confidence Level 4, Square = Confidence Level 3. Although no 1956 surfaces were visited in this reach, it is estimated that the fine mantle thickness for these surfaces was around 0.3 m-0.4 m.

avulsion occurred, occupying a channel near the road, and leaving multiple channels apparently active. By 1956, the median channel width narrowed by 15 m and the wider portions of the reach narrowed by 13.5 m (Figure 1.31). The 1956 air photos show sediment deposits/mid-channel bars throughout the channel and a vegetated island still present (Figure 1.30). Even with the occurrence of the 1952 flood, the 1939 channel and the 1956 channel were at similar elevations based on 1939 and 1956 relict surfaces both at 2.0 m above the modern channel (Figure 1.29).

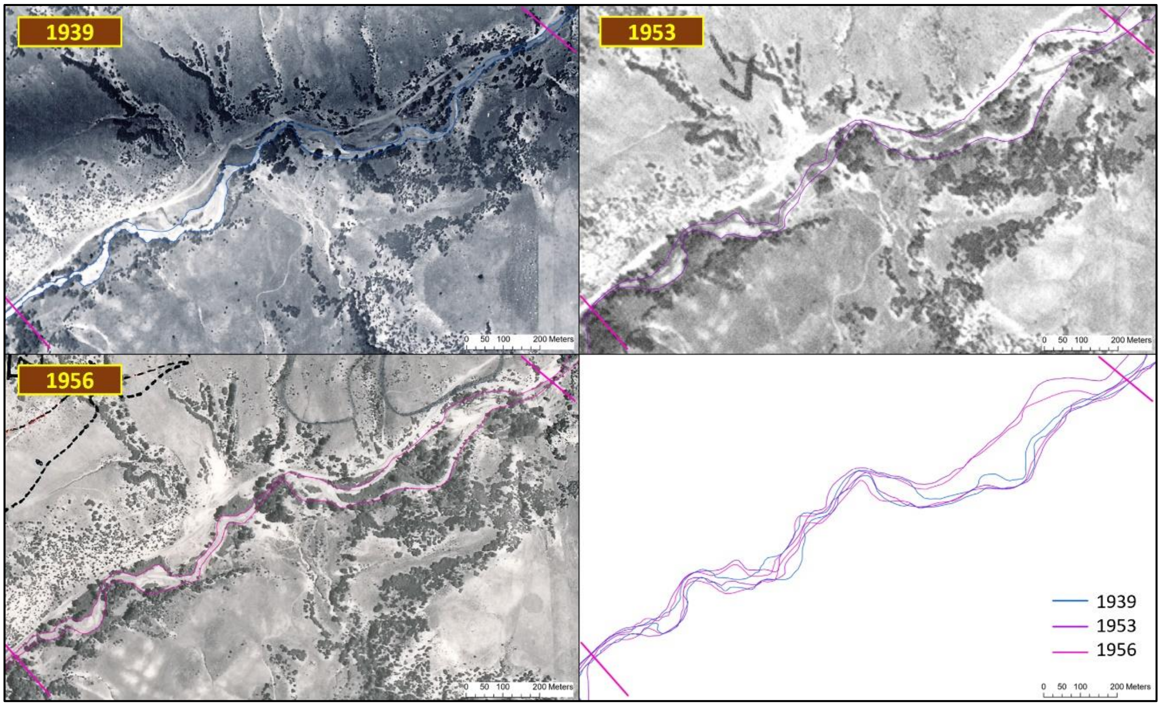

Figure 1.30. Air photos of BBH Reach: 1939 to 1956 including active channel margins in 1939, 1953, and 1956. The active channel widened significantly from 1939 to 1953 due to an avulsion that occurred during the 1952 flood. Narrowing began by 1956.

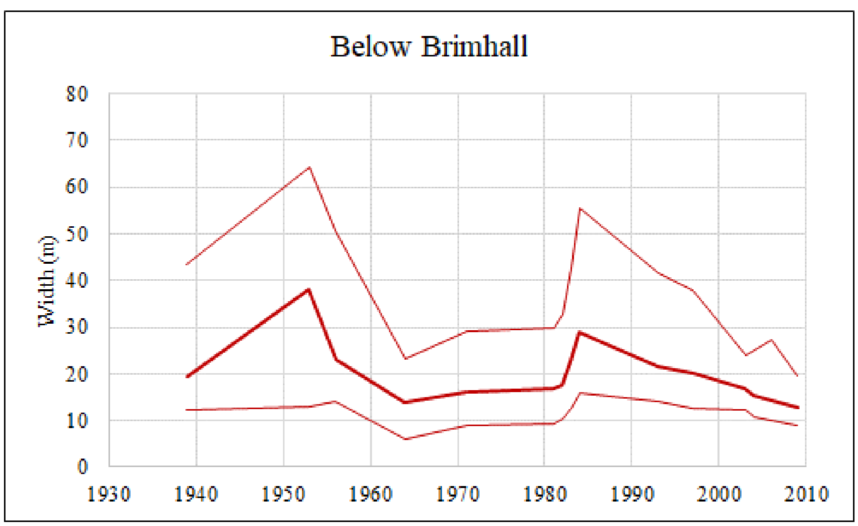

Figure 1.31. 10th percentile, median, and 90th percentile widths of Below Brimhall reach from 1939-2009. Increases in width in 1952 and 1984 were due to the two large natural floods during these years.

Channel avulsion remained a persistent attribute for much of the reach with the channel switching between the right and left sides of the valley bottom through the 20th century. Evidence of multiple paths in 1939 included small side channels present in the upstream section and in the downstream section suggesting that the channel had also avulsed before 1939. Vegetated islands were also present demonstrating that the channel avulsed sometime before 1939 (Figure 1.30). Subsequent channel switching occurred between 1956 and 1964 causing the main channel to shift from left to right (Figure 1.32) and narrowing the median channel width from 23 m to 14 m and the 90th percentile width from 51 m to 23 m (Figure 1.31). No relict surfaces remain from the 1964 channel position and only one relict surface is present that represents the 1971 channel in this reach. The 1971 channel followed a similar pattern to the 1964 channel demonstrated by both channels being single thread and meandering (Figure 1.32). Based on the air photos, a larger amount of mature vegetation was observed on the banks next to the 1971 channel compared to the channel in 1964 (Figure 1.32).

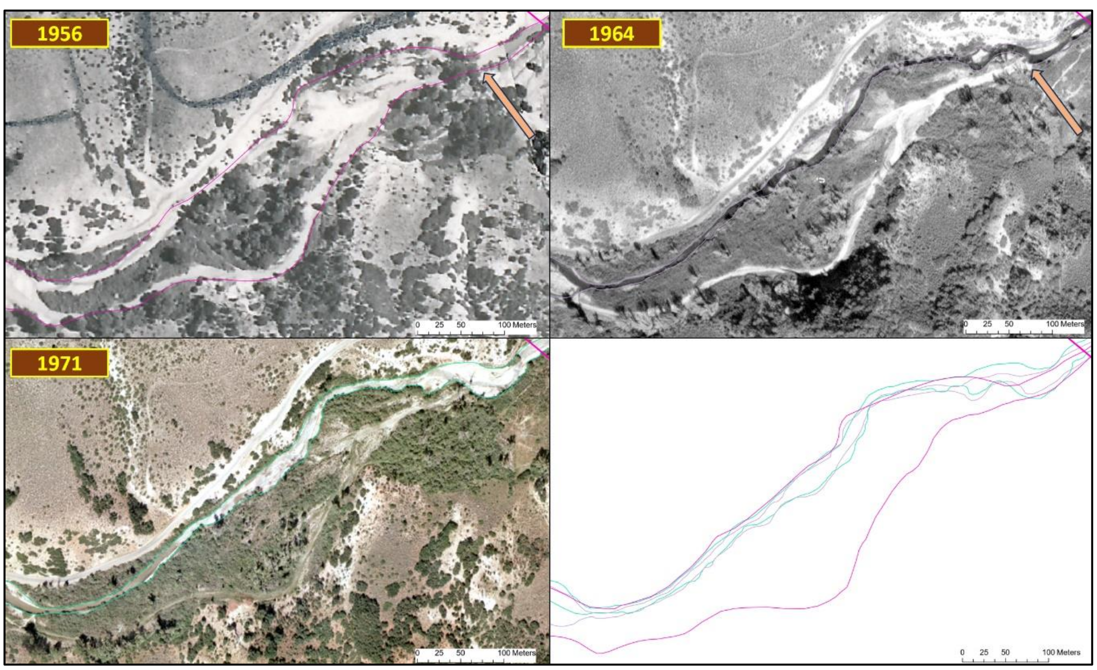

Figure 1.32. Air photos of BBH Reach: 1956-1971. The orange arrow points to the avulsion between 1956 and 1964 which caused the channel to switch sides. Lines depict active channel boundaries.

Between 1983 and 1984, another avulsion occurred at the top of the reach due to the 1984 flood, which caused the main channel to switch back to river left. This flood eliminated vegetation in the area (Figure 1.33), widening the median channel from 23 m in 1983 to 29 m in 1984 (Figure 1.31). The wider sections of the channel also widened significantly with the 90th percentile width increasing by 26 m since 1981 (Figure 1.31). Quite a few 1984 relict surfaces in this reach were vegetated by 1993, suggesting that the channel cut down between 1984 and 1993. The 1993 relict surfaces were relatively lower in elevation compared to the 1984 relict surfaces (Figure 1.29), further providing evidence that the channel cut down between those two years.

A final avulsion occurred in 1993 a bit downstream from the first two avulsions causing the channel to move back to river right, where it remains today (Figure 1.33). Bend growth and channel migration have continued since the removal of diversion flows producing post-project

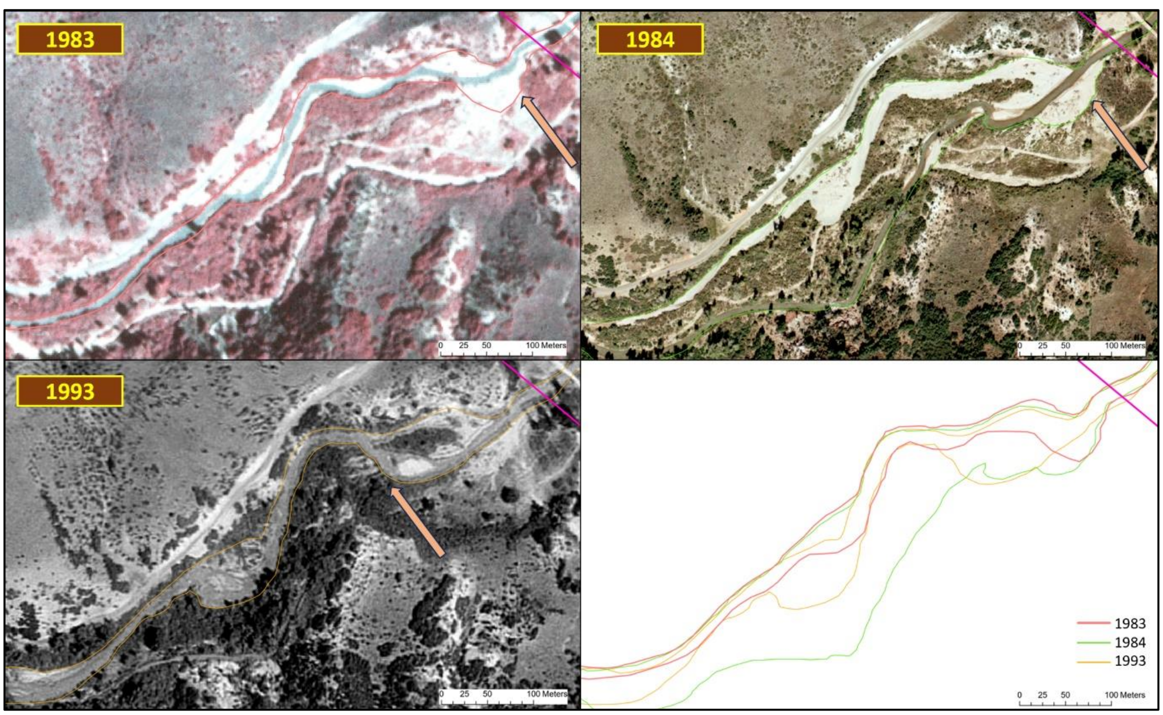

Figure 1.33. Air photos of BBH Reach: 1983-1993. The orange arrow points out the avulsions between 1983 and 1984 and then between 1984 and 1993 which caused the channel to switch sides. Lines depict active channel boundaries.

relict surfaces in this reach. These surfaces can be described as fluvial surfaces formed after 2003. Overall, the channel planform has stayed similar in the downstream section of this reach based on the minimal number of 1930s-1970s relict surfaces. It is inferred that the river was consistently shifting and reworking during these years and did not create any relict fluvial surfaces until the 1980s as demonstrated by air photos.

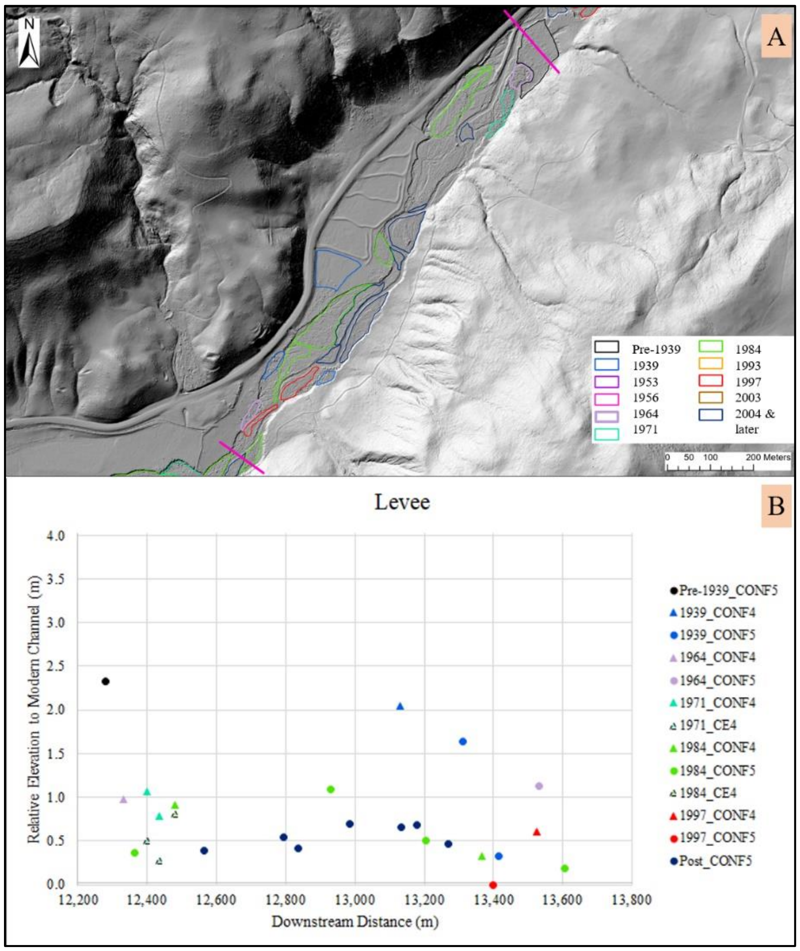

Figure 1.34. Levee Reach: (A) DEM hillshade showing relict surfaces. (B) Relative elevation of relict surfaces with confidence mapping levels. CONF# = Mapping confidence level of surface. CE# = Corrected elevation of abandoned surface to account for thickness of fine mantle data collected in the field. Circle = Confidence Level 5, Triangle = Confidence Level 4.

4.8 Levee (Reach 8)

The LDFK in the 1.4 km Levee (LV) reach has a 0.6% slope (Table 1.1) and is unconfined but constrained by the Diamond Fork Road on the right and terraces on the left (Figure 1.34). The channel is largely single thread with a broad braid plain occupying most of this reach throughout the project period. The riverbed is coarse gravel with some mobile sediment in the present regime.

The river bed likely aggraded in the early decades of the project, based on a relict surface just over 2.0 m above the modern channel (Figure 1.34). A side channel evident in 1939 (Figure 1.35) was abandoned in later years, suggesting some channel downcutting after 1939. The median active channel width during this time was 45 m due to a broad braid plain occupying about 45% of the reach (Figure 1.35, Figure 1.36).

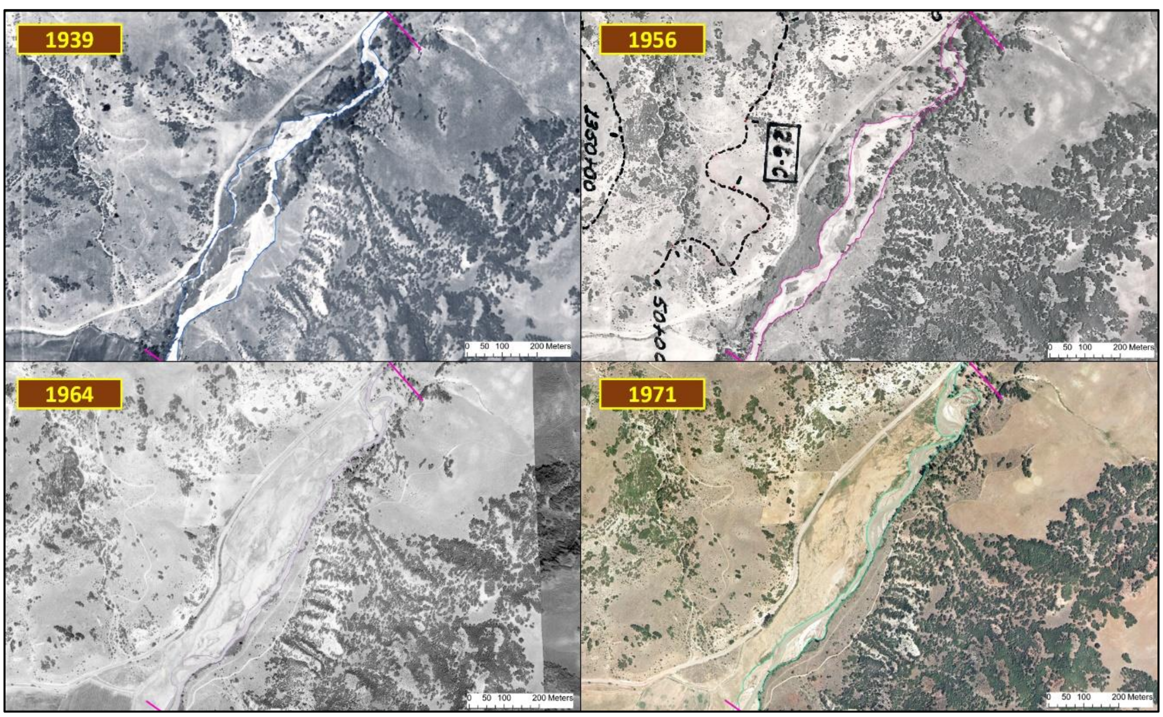

Figure 1.35. Air photos of LV Reach: 1939-1971. The side channel in 1939, the aftermath of the 1952 flood in 1956, a diverted channel in 1964, and how the channel began to braid in 1971 can be seen here. Lines depict active channel boundaries.

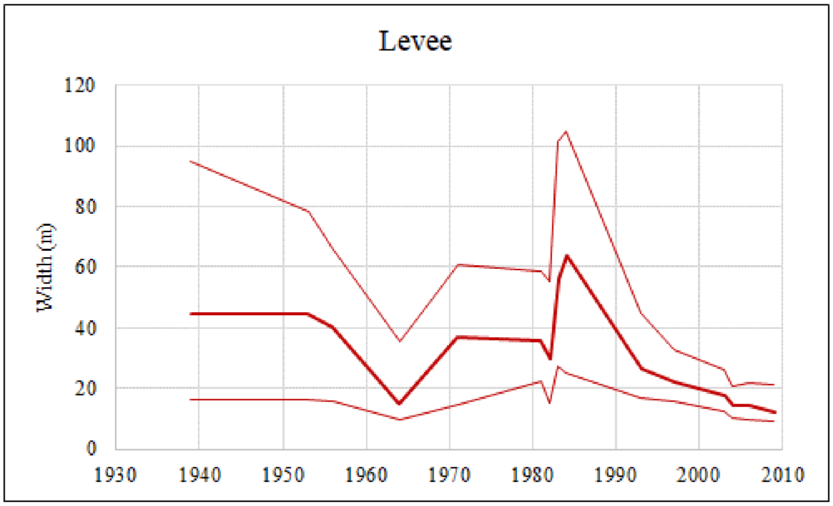

Figure 1.36. 10th percentile, median, and 90th percentile widths of Levee reach from 1939-2009. Increases in width in 1952 and 1984 were due to the two large natural floods during these years.

The flood of 1952 straightened the channel and narrowed the wider portions of the reach by 16.5 m; however, it did not change the median channel width of the reach or allow the formation of any relict surfaces (Figure 1.35, Figure 1.36). About 45% of the LDFK channel was braided in 1956 with sediment deposits/mid-channel bars found throughout the reach (Figure 1.35). In 1964, the channel was forced into a nearly straight channel along river left and the new right-bank was cleared of trees (Figure 1.35). This made the channel significantly straighter, narrowing the median channel width to 15 m, and the 90th percentile width to 36 m (Figure 1.36), but only shortening the channel by 10 m since 1956. A few bends were still present in the most upstream and most downstream ends of the 1964 channel, which added length causing the channel to not shorten a significant amount even with channel straightening.

In 1971, large gravel bars began to form in the straightened reach, causing the channel to become multi-threaded (Figure 1.35). In 1981, 80% of the channel was braided with braiding decreasing to 70% in 1982. A single thread channel was present in 1983 (Figure 1.37).

After the 1984 flood, a levee was built to prevent erosion of Diamond Fork Forest Road. This straightened the upstream section of the channel but did not impact the overall channel length. The 1984 flood caused the median active channel width to increase by 28 m and the

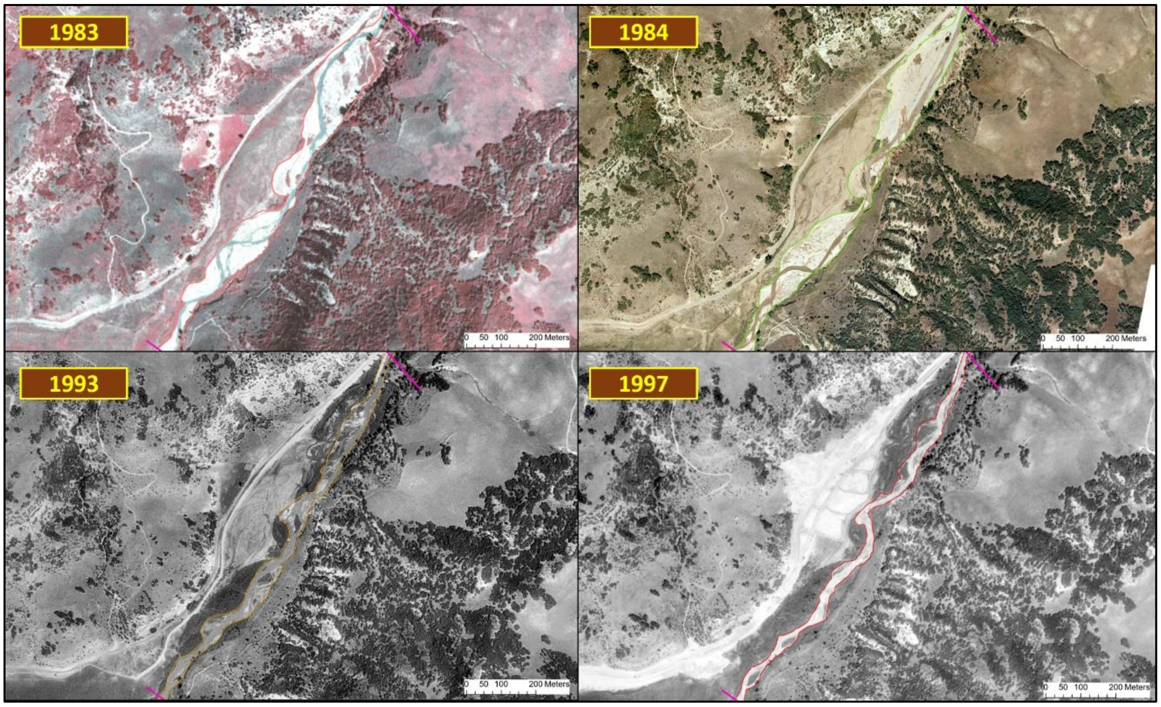

Figure 1.37. Air photos of BBH Reach: 1983-1997. A levee was built in 1984, straightening the channel, with part of the levee breaching by 1993 allowing the channel to create meander bends. Lines depict active channel boundaries.

widest sections of the channel to double in width since 1981 (Figure 1.36). After the 1984 flood, the active channel width significantly decreased with the median active channel width and the widest parts of the channel decreasing by almost a factor of 2.5. Part of the downstream end of the levee breached before 1993 when the channel began to meander. (Figure 1.37).

There has been no elevation change since 1984, as indicated by the fact that portions of the 1984 channel protected by the levee are at the same elevation as the modern channel (Figure 1.34). After the removal of the diversion flows in 2004, the channel has remained single thread with a few slight meander bends. The channel planform has not changed substantially since 2004.

4.9 Motherlode (Reach 9)

The LDFK channel in the 1.4 km Motherlode (MO) reach has a 0.6% slope (Table 1.1) and is unconfined (Figure 1.38). A broad braid plain occupied most of this reach throughout the project period. A single thread channel has developed in recent decades, even though the limited

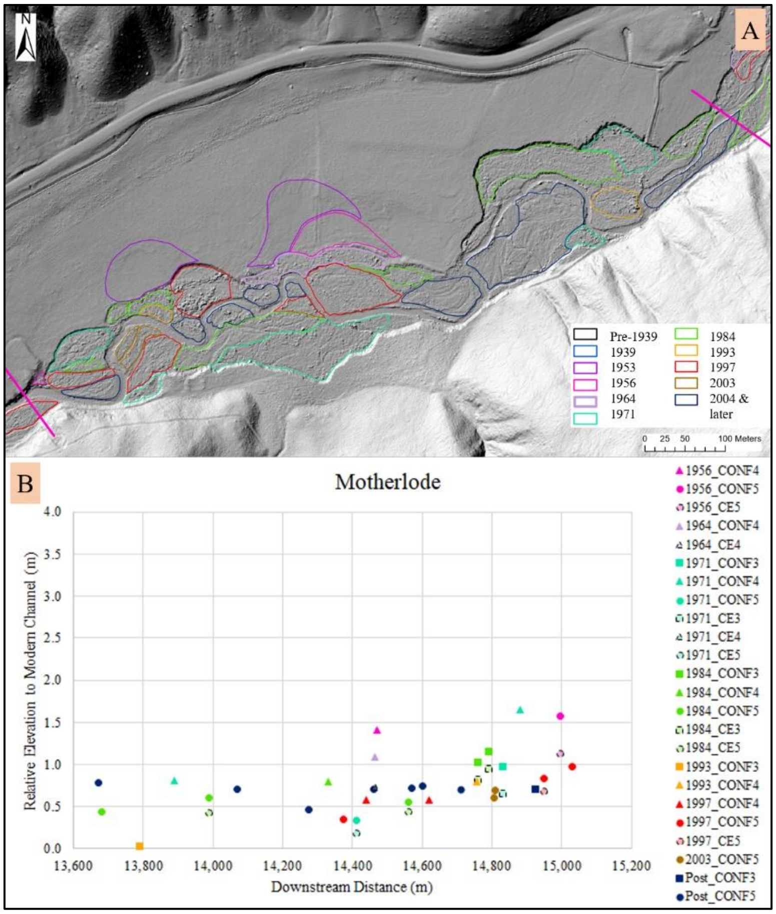

Figure 1.38. Motherlode Reach: (A) DEM hillshade showing relict surfaces. (B) Relative elevation of relict surfaces with confidence mapping levels. CONF# = Mapping confidence level of surface. CE# = Corrected elevation of abandoned surface to account for thickness of fine mantle data collected in the field. Circle = Confidence Level 5, Triangle = Confidence Level 4, Square = Confidence Level 3.

lateral topography across the former braid plain remains (Figure 1.38). The riverbed is medium to coarse gravel with some mobile sediment in the present regime.

In 1939 the channel was single thread, meandering, with a mature riparian corridor, (Figure 1.39) and a median width of 16 m (Figure 1.40). There is an indication of a pre-1939 large bend on river right in the 1939 air photo. This bend and more were reoccupied by the 1952 flood, when the river cut two large bends to river right and widened the median channel width by a factor of two and the wider portions of the channel by a factor of 2.5 (Figure 1.39, Figure 1.40). These large bends were cut off by 1956 which significantly straightened the channel, narrowed

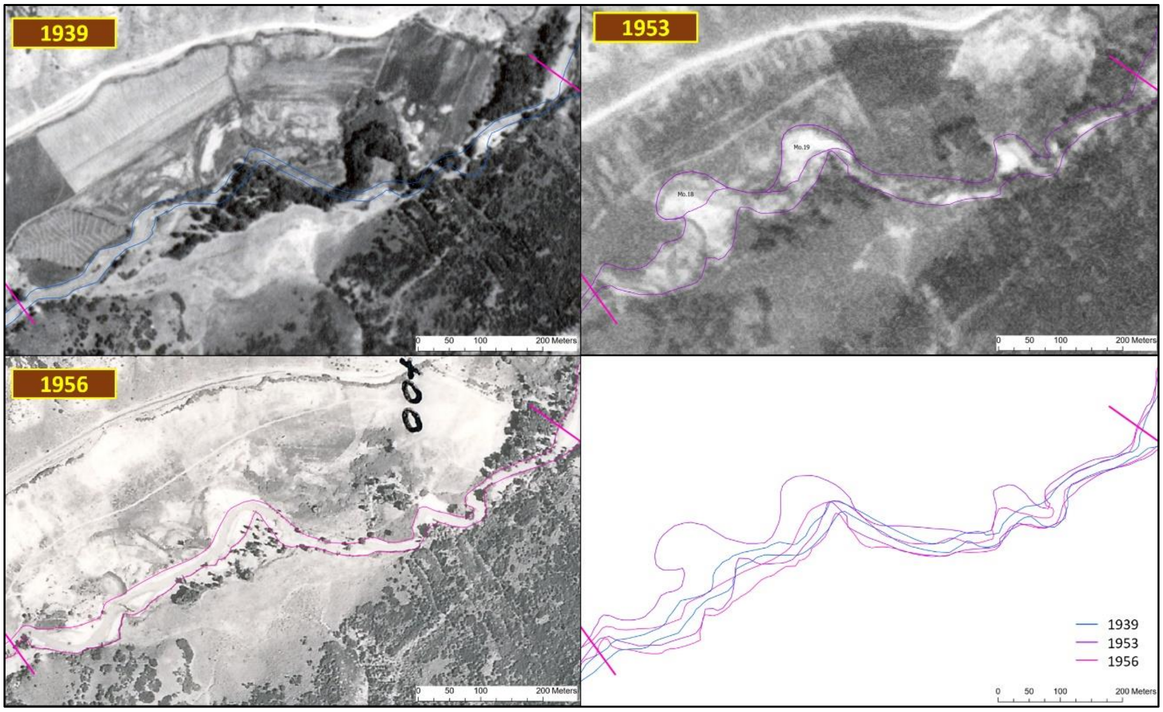

Figure 1.39. Air photos of MO Reach: 1939-1956. The 1952 flood produced two large bends and that were then cut off by 1956. Lines depict active channel boundaries.

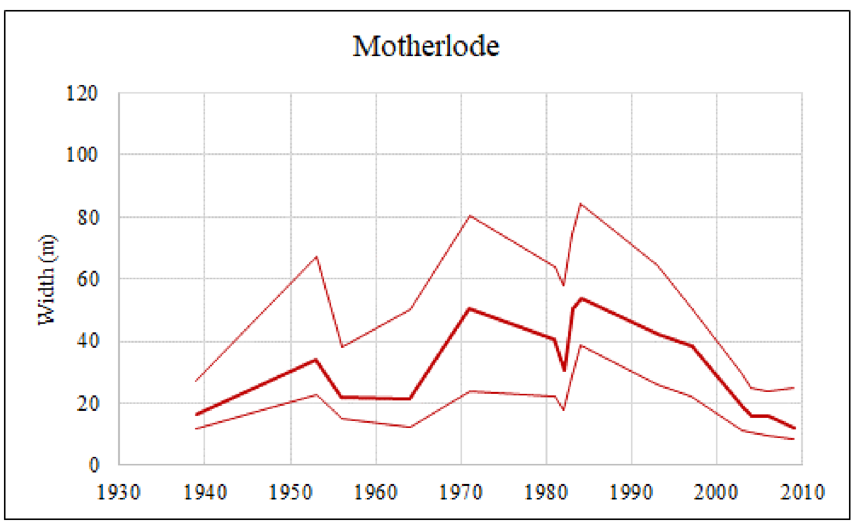

Figure 1.40. 10th percentile, median, and 90th percentile widths of Motherlode reach from 1939-2009. Increases in width in 1952 and 1984 were due to the two large natural floods during these years.

the median width by 12 m, narrowed the 90th percentile width by 29 m, and shortened the channel by 30 m (Figure 1.39, Figure 1.40).

By 1964, three small bends were cut off by the channel leaving behind a relict surface about 1.5 m above the modern channel, but decreasing overall channel length by only 7 m. About 70% of the channel was single thread at this time, with the remaining 30% of the channel braided during that year. Extensive channel change occurred in 1971 due to lateral cutting on river left which increased median channel width by 30 m and the wider portions of the channel also by 30 m (Figure 1.40). About 80% of the channel was left braided with mid-channel bars throughout this reach (Figure 1.41). Much of the 1971 braid plain was vegetated by 1981. The median active channel width decreased by 10 m between 1971 and 1981 (Figure 1.40) allowing vegetation to establish since water was no longer occupying that area (Figure 1.41).

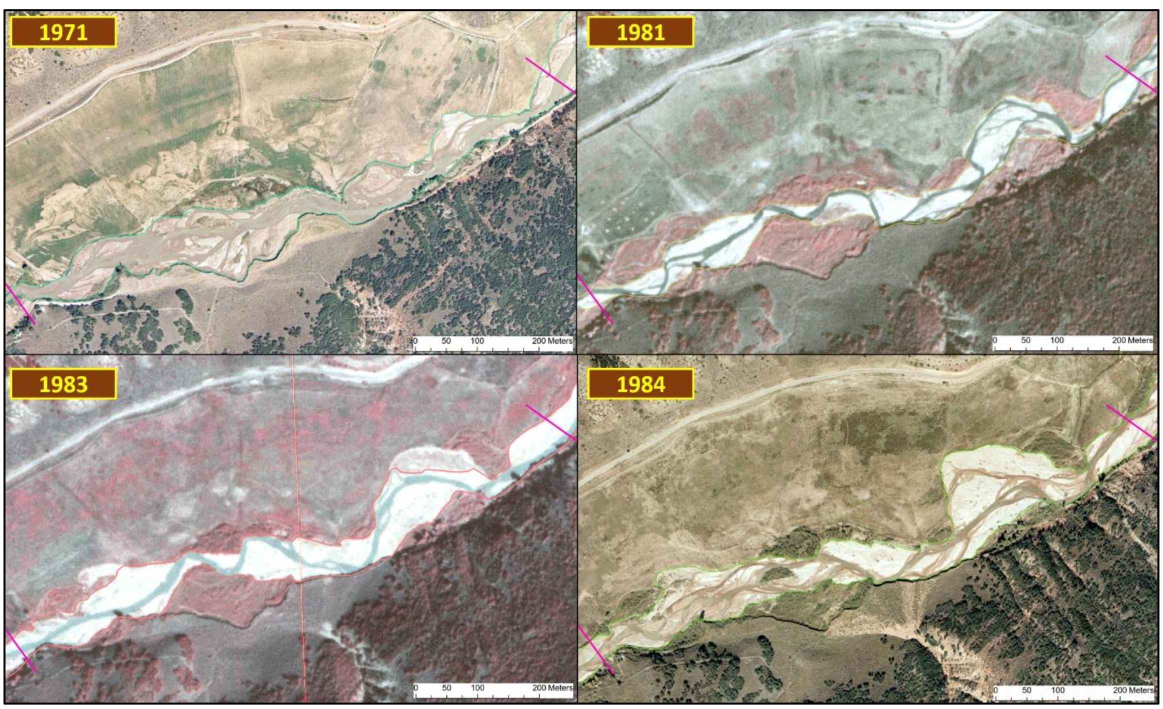

Figure 1.41. Air photos of MO Reach: 1971-1984: Changes in the amount of braiding that occurred from 1971-1984. Lines depict active channel boundaries.

The extent of braiding in the reach decreased from 65% in 1981 to 20% in 1983 (Figure 1.41). After the 1984 flood, the channel was back up to almost 80% braided with evidence of some lateral cutting in the upstream section (Figure 1.41). Vegetation along the banks was removed by the 1984 flood, widening the median active channel significantly to its greatest width of 54 m and a 90th percentile width of 84 m (Figure 1.40). This flood also caused gravel bars to be left behind (Figure 1.41). Many of these bars were vegetated by 1993 and the median active channel narrowed by 12 m with the wider portions of the channel narrowing by 19.5 m (Figure 1.40). Vegetation was able to grow (Figure 1.42) even with the elevation of these surfaces being quite similar to the elevation of the modern channel (Figure 1.38). Mid-channel bars can still be found throughout the channel in 1993. The active channel was still wide with about 95% of the reach braided until 1997 (Figure 1.42). After that, the channel narrowed by 50% (Figure 1.40) and became mostly single thread in 2003 (Figure 1.42). As the channel has become dominantly single thread, the broad braid plain has become vegetated and relict surfaces have little difference in elevation from the modern channel (Figure 1.38).

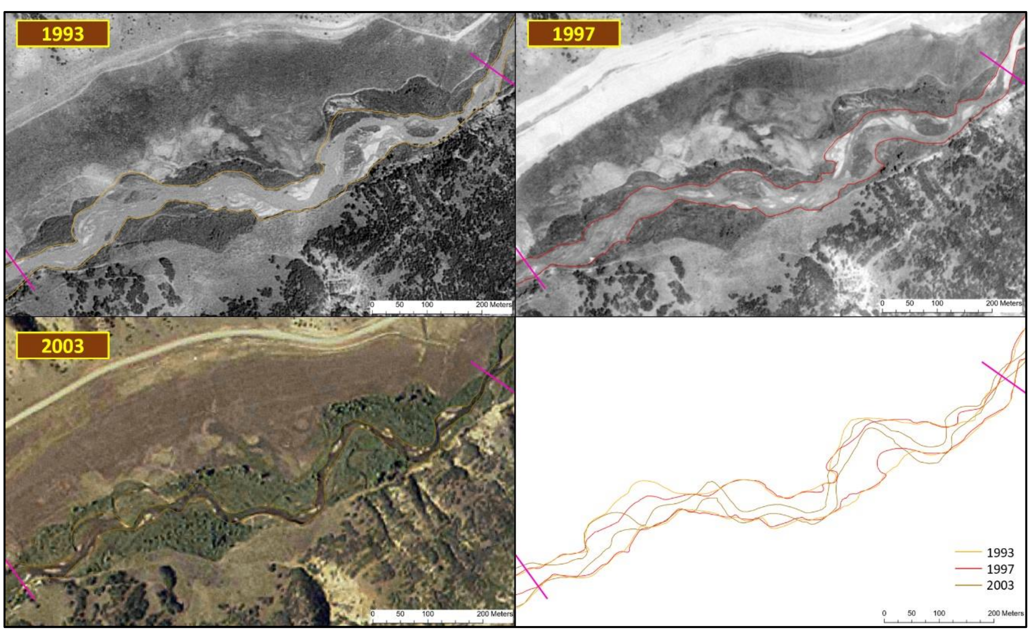

Figure 1.42. Air photos of MO Reach: 1993-2003. Channel braiding in 1993 and 1997 and then a single-thread and significantly narrower channel in 2003. Lines depict active channel boundaries.

4.10 Upper Oxbow and Lower Oxbow (Reaches 10 and 11)

The LDFK in the 1.3 km upper (UOX) and lower (LOX) Oxbow reaches has a 0.7% slope in the upstream section of the reach and a 0.6% slope in the downstream section of the reach (Table 1.1) and is largely unconfined (Figure 1.43, Figure 1.44). The riverbed is medium to coarse gravel with some mobile sediment in the present regime.

A possible fluvial surface (Ox. 24) almost 4.0 m above the modern channel is evident in the LiDAR DEM (Figure 1.43). The surface looks like it was cut by the river and was already forested in the first air photos in 1939. A distinctive v-shaped meander bend (Ox. 2), 2.0 m above the modern channel, was clearly occupied by the 1939 channel (Figure 1.44) and cut off by the 1952 flood. A higher channel position early in the project period is likely although the extent of the elevation difference is not fully certain.

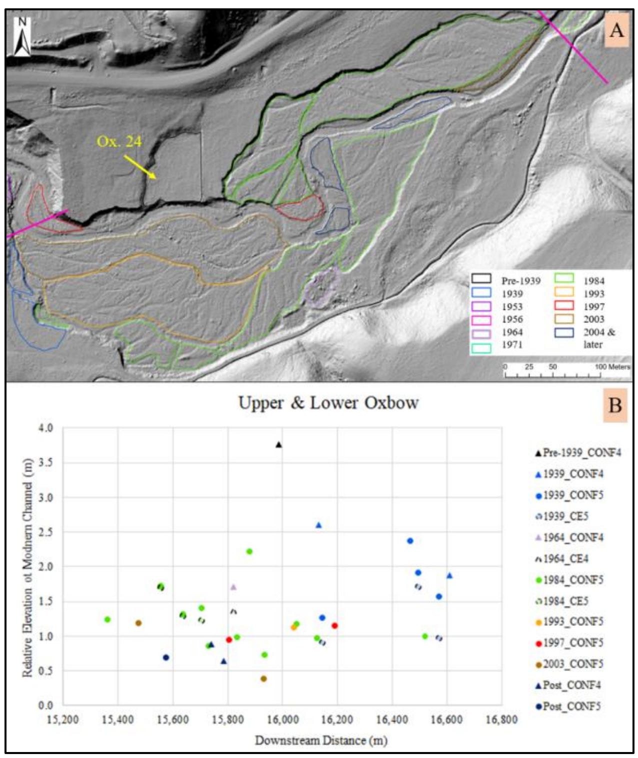

Figure 1.43. Upper Oxbow Reach (15,200 m – 16,160 m): (A) DEM hillshade showing relict surfaces. (B) Relative elevation of relict surfaces with confidence mapping levels. CONF# = Mapping confidence level of surface. CE# = Corrected elevation of abandoned surface to account for thickness of fine mantle data collected in the field. Circle = Confidence Level 5, Triangle = Confidence Level 4.

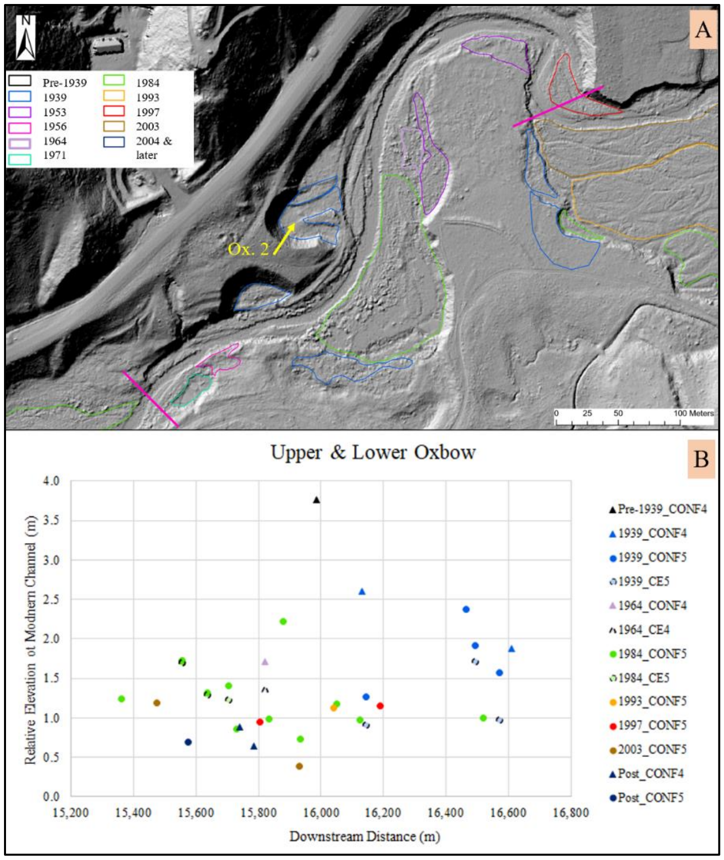

Figure 1.44. Lower Oxbow Reach (16,160 m – 16,720 m): (A) DEM hillshade showing relict surfaces. (B) Relative elevation of relict surfaces with confidence mapping levels. CONF# = Mapping confidence level of surface. CE# = Corrected elevation of abandoned surface to account for thickness of fine mantle data collected in the field. Circle = Confidence Level 5, Triangle = Confidence Level 4.

The 1939 channel was a single thread, meandering channel with mature trees along the banks (Figure 1.45). The median river width was 13 m in upper Oxbow and 15 m in lower Oxbow (Figure 1.46, Figure 1.47). The 1952 flood cut off three bends in the 1939 channel, straightened the downstream section of this reach and caused the channel to cut down. This flood also widened the active channel through the deposition of gravel bars. Widening was especially apparent in the wider sections of Oxbow reach with these portions widening by 30 m in both the downstream and upstream sections. The 1956 channel was single thread and meandering with small mid-channel bar deposits that were spread throughout this reach (Figure 1.45).

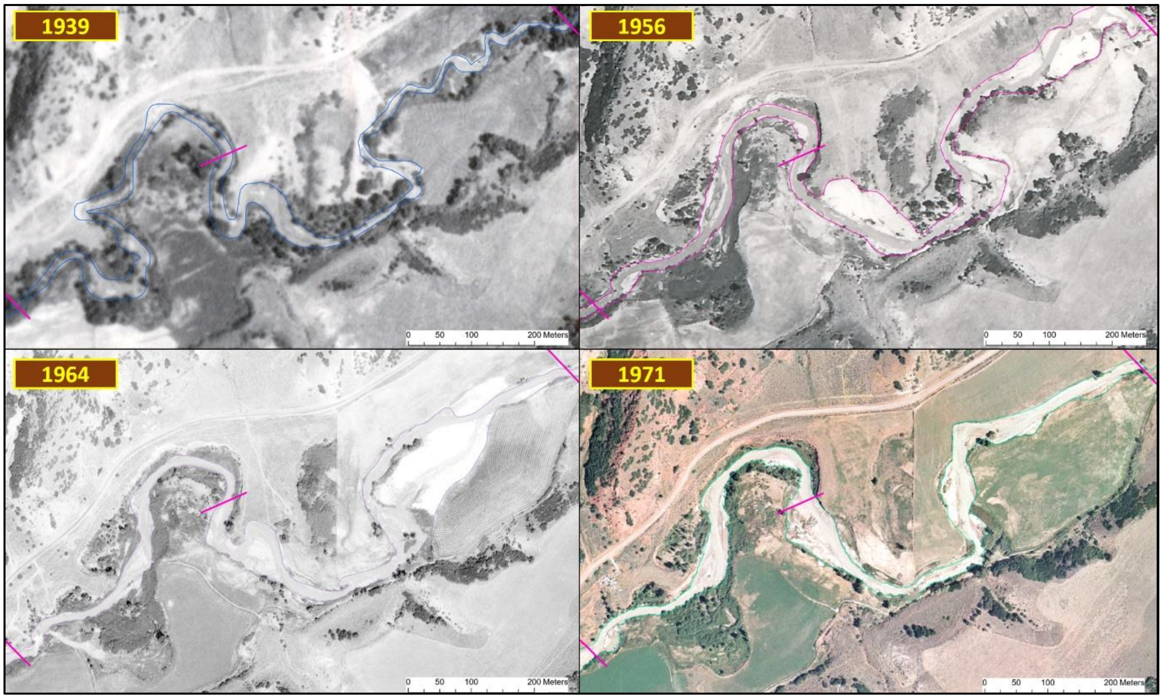

Figure 1.45. Air photos of UOX and LOX Reaches: 1939-1971. Between 1939 and 1956, the 1952 flood straightened the channel by cutting off 3 bends. The channel then straightened again between 1964 and 1971. Lines depict active channel boundaries.

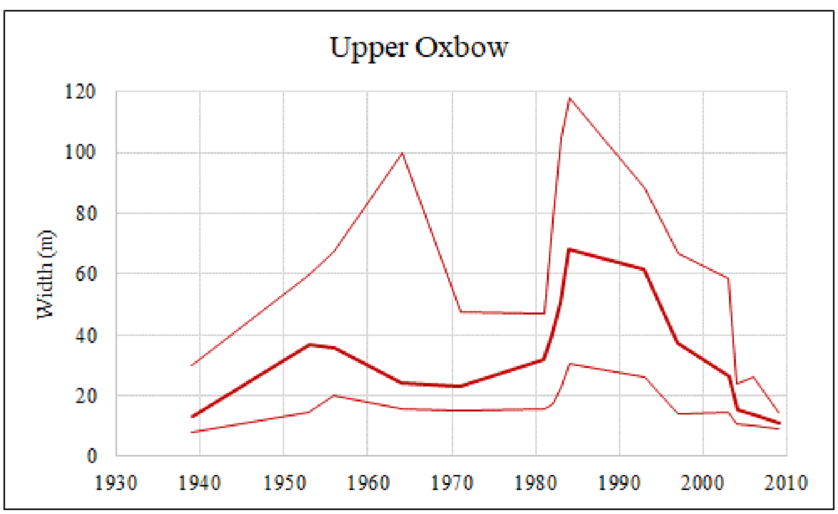

Figure 1.46. 10th percentile, median, and 90th percentile widths of upper Oxbow reach from 1939-2009. Increases in width in 1952 and 1984 were due to the two large natural floods during these years.

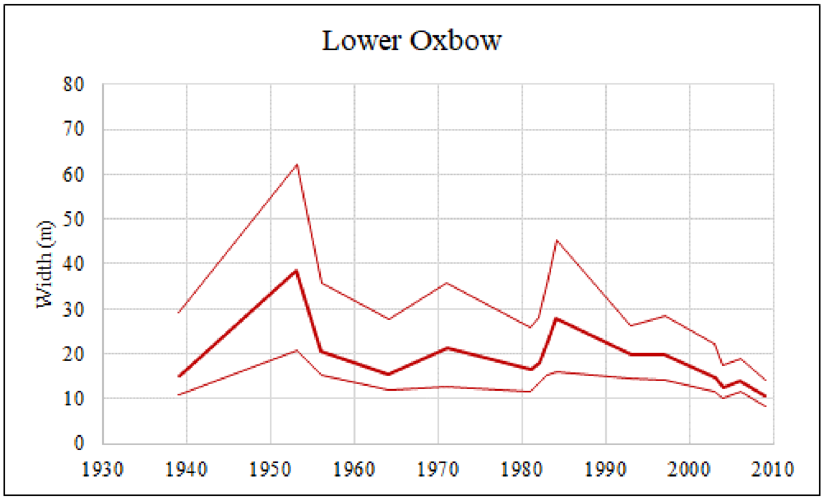

Figure 1.47. 10th percentile, median, and 90th percentile widths of lower Oxbow reach from 1939-2009. Increases in width in 1952 and 1984 were due to the two large natural floods during these years.

By 1981, the LDFK began to slightly widen with about 35% of the channel braided from 1981-1982. The 1983 and 1984 floods removed riparian vegetation leaving behind unvegetated surfaces next to the channel which widened the active channel throughout the Oxbow reach (Figure 1.46, Figure 1.47). Specifically in the upstream portion of the reach, these floods caused the median channel width to widen 28 m and the wider sections of the reach to widen 40 m between 1982 and 1984 (Figure 1.46). Although flowing through a broad braid plain with little lateral relief, a well-defined single thread channel is clearly evident in the air photos. Channel shifting occurred in the 1984 flood, shifting the main channel back to river right (Figure 1.48). This flood created a large point bar on the lower section of the reach, causing this area of the channel to become more sinuous.

By 1993, the channel began to narrow again with about 50% of upper Oxbow braided until 1997 when Syar tunnel became operational (Figure 1.48). In 2004, the diversion flows were removed from LDFK, and channel was single thread once again (Figure 1.48). Overall, more narrowing occurred in the upper section of Oxbow compared to the lower section. The upper

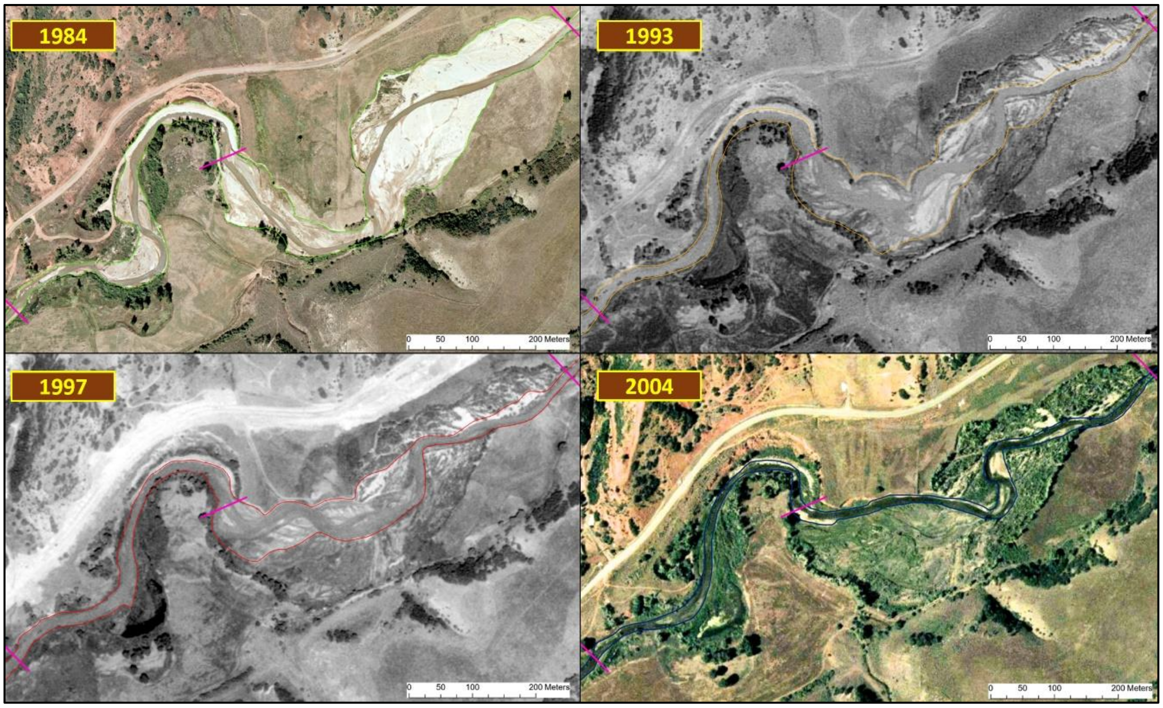

Figure 1.48. Air photos of UOX and LOX Reaches: 1984-2004: Diverse channel change occurred from 1984 to 2004 due to the 1984 flood and then the removal of the diversion flows from the channel in 2004. Lines depict active channel boundaries.

section of this reach is located in a broad braid plain, which likely allowed the channel more room to shift laterally.

4.11 Upper and Lower Childs (Reaches 12 and 13)

The LDFK in the 1.5 km Childs (CH) reach is the furthest downstream reach and closest to the mouth of the river. The distance from the bottom of the reach to the confluence with Spanish Fork River is roughly 0.6 km. This reach has a 0.5% slope (Table 1.1) and is unconfined (Figure 1.49). The channel is largely single thread and has been throughout the project period. The riverbed is medium to coarse gravel with some mobile sediment in the present regime.

Base level control was provided by Spanish Fork River in the early years of the project. At later dates, base level control may have shifted to 400 m downstream of the reach with ongoing development of a road crossing. A modern highway bridge with an unknown riverbed control was built between 1953 and 1956. In 1983, base level control shifted to 100 m

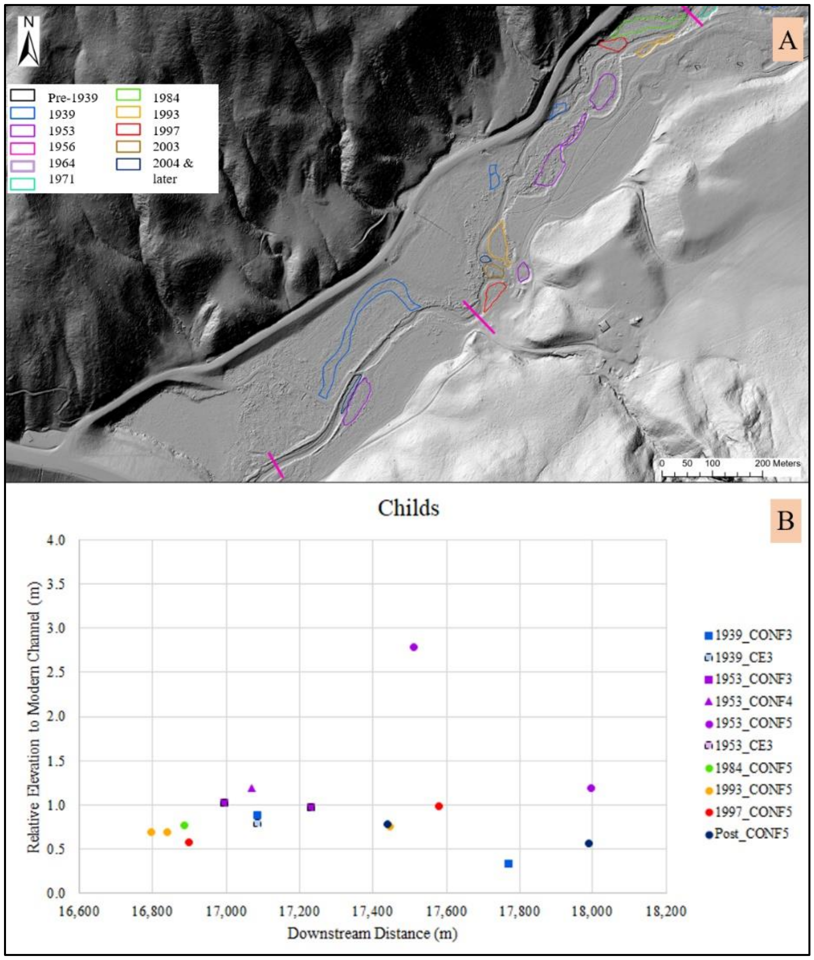

Figure 1.49. Upper and Lower Childs Reach: (A) DEM hillshade showing relict surfaces. (B) Relative elevation of relict surfaces with confidence mapping levels. CONF# = Mapping confidence level of surface. CE# = Corrected elevation of abandoned surface to account for thickness of fine mantle data collected in the field. Circle = Confidence Level 5, Triangle = Confidence Level 4, Square = Confidence Level 3.

downstream of the reach with construction of culverts through the modern embankment of Highway 6.

In 1921, a report by W.L. Whittemore of the Bureau of Reclamation documented extensive deposition of a delta on the Hayes Farm, now largely underneath the Highway 6 embankment. Whittemore attributed the aggradation to a large pool on the Spanish Fork River, caused by backwater from a channel constriction due to uncompleted river modifications as part of relocating the Denver and Rio Grande railroad tracks in 1914. Beyond the aggradation of uncertain and possibly exceptional cause, the 1939 air photos show a single thread, meandering channel with mature trees along its banks (Figure 1.50). The median river width was 15 m, compared to an estimated width of 8.1 m for natural channels in the area with similar drainage area (Jones et al., 2023), Figure 1.51). Diversion flows over 23 years produced complaints of flooding and likely channel widening, but the river channel appeared to remain within its riparian corridor.

The 1952 flood produced considerable channel change. The riparian corridor of large trees was largely removed (Figure 1.50). In upper Childs, the full meander belt was occupied by unvegetated, bare sediment and by 1956, a well-defined and nearly straight channel had developed (Figure 1.50). In lower Childs, the river avulsed from a distinct, rightward bend and established a new, straight, and shorter channel to the road crossing 400 m downstream. The road crossing and bridge appeared to have survived the 1952 flood and the degree of vertical control provided by the crossing is unknown. Between 1953 and 1956, the road was moved just downstream and crosses over what may have been two large culverts. The mapped channel width in 1953 was considerably wider than in 1939 or 1956, especially in the wider portions of the channel, and likely included overbank areas devoid of vegetation (Figure 1.51). The channel shortened by 20% from 1939 to 1956, from three bends cutoffs and an avulsion straightened the channel. Channel incision was likely although the extent is difficult to judge. 1939 and 1953 relict surfaces were no more than 1.0 m above the modern channel with one exception (Figure 1.49). A surface that was laterally eroded in the 1952 flood was almost 3.0 m above the modern channel (Figure 1.49). Part of this surface may have been cut early in project history before the channel shifted to its 1939 location. During the 1952 avulsion, the channel reoccupied this surface and may have laterally enlarged it before cutting to its post-flood elevation.

The channel in the Childs reach remained relatively straight without large changes in width throughout the remainder of the project period. A large, broad bend crossing from upper to lower Childs sharpened and produced some outward migration, threatening a farm road. The

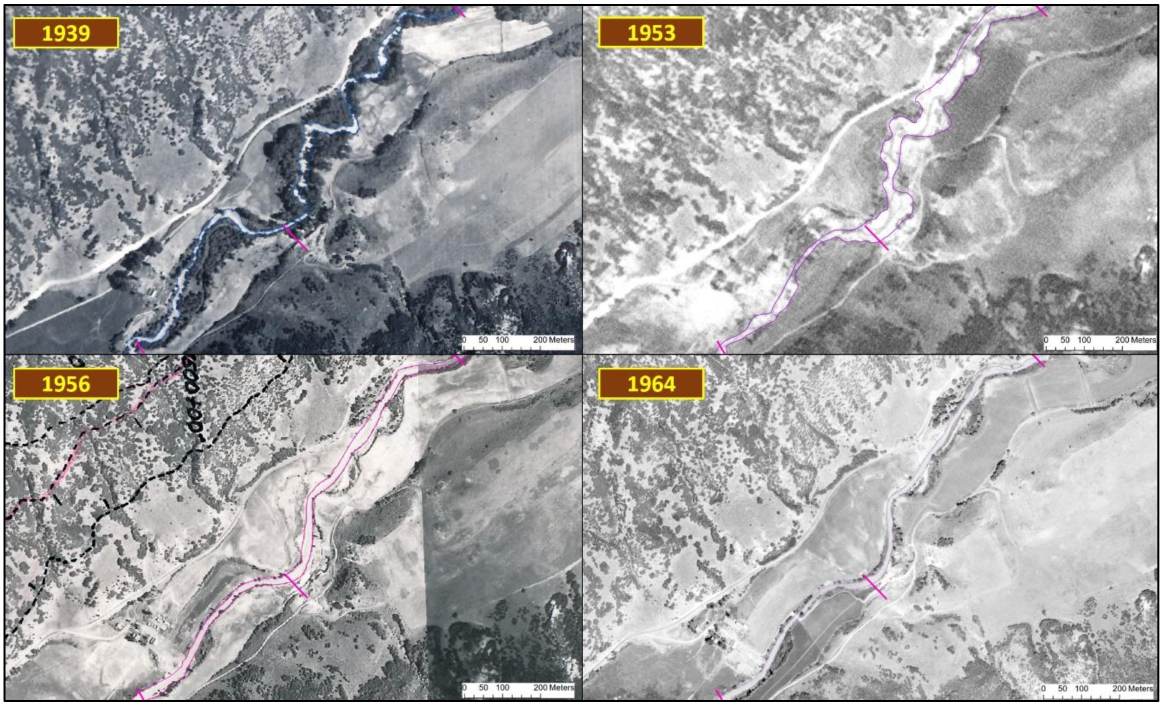

Figure 1.50. Air photos of CH Reach: 1939-1964. The channel shortened by 20% from 1939 to 1956, suggesting that the large flood, tree removal, and avulsion produced a steeper channel. Lines depict active channel boundaries.

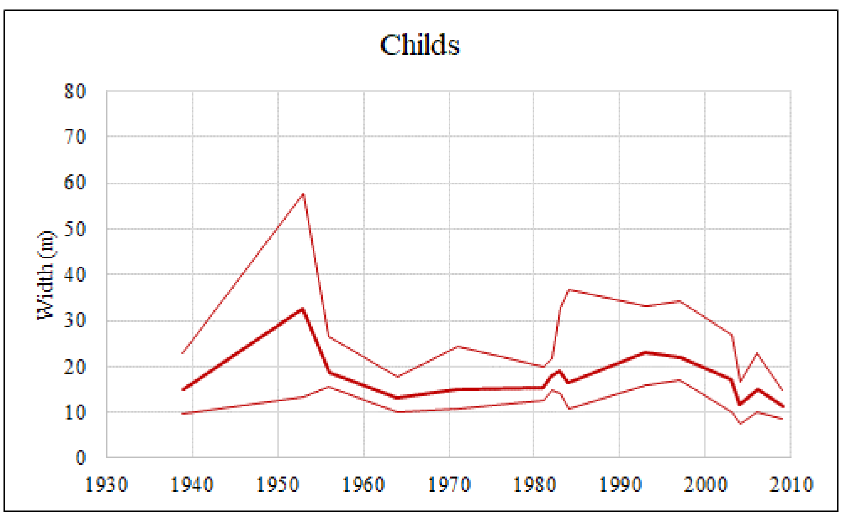

Figure 1.51. 10th percentile, median, and 90th percentile widths of upper and lower Childs reach from 1939-2009. Increases in width in 1952 and 1984 were due to the two large natural floods during these years.

Figure 1.52. Air photos of CH Reach: 1983-2004. The 1983 and 1984 floods removed some riparian vegetation, producing an apparent widening of the channel in locations. Lines depict active channel boundaries.

1983 and 1984 floods removed some riparian vegetation, producing an apparent widening of the channel in locations, although the median width of the main channel did not appear to have changed significantly (Figure 1.51, Figure 1.52).

After diversion flows were removed from the river in 2004, the channel narrowed, and sinuosity increased. Overall, the average elevation of the relict surfaces from 1939 to post-2004 was consistently around 0.5 m – 1.0 m above the modern channel, suggesting that there was not much vertical and instead more lateral change in this reach of the LDFK (Figure 1.49).

5. Discussion

The goal of this study is to document how the lower Diamond Fork River responded to 87 years of an exceptionally large flow augmentation. Although the flow augmentation was larger than most natural floods, two floods, in 1952 and 1984 were roughly three times larger than the peak diversion flows. The focus questions of this study are: How did channel width, pattern, and elevation change in response to flow augmentation? What impact did the 1952 and 1984 floods have on the longer-term trends of channel response to flow augmentation? Air photos are used to evaluate historical conditions, providing information on channel width and pattern as well as some indication of the near-channel vegetation. We identified surfaces that were abandoned by the river and preserved to the present. Using a 2017 LiDAR DEM, we could then estimate the elevation of those surfaces relative to the modern channel.

5.1 Key Observations

The style and magnitude of channel response to flow augmentation and associated sediment supply differed in the study area due to differences in valley confinement and distance downstream. In this section, we place reach-by-reach channel changes in a broader context. Figure 1.53 presents the mean channel width of all 13 reaches on the lower Diamond Fork for all air photos through the project period. Figure 1.54 provides the same information for fewer years that bracket the project period and the 1952 and 1984 floods. Figure 1.55 gives the relative

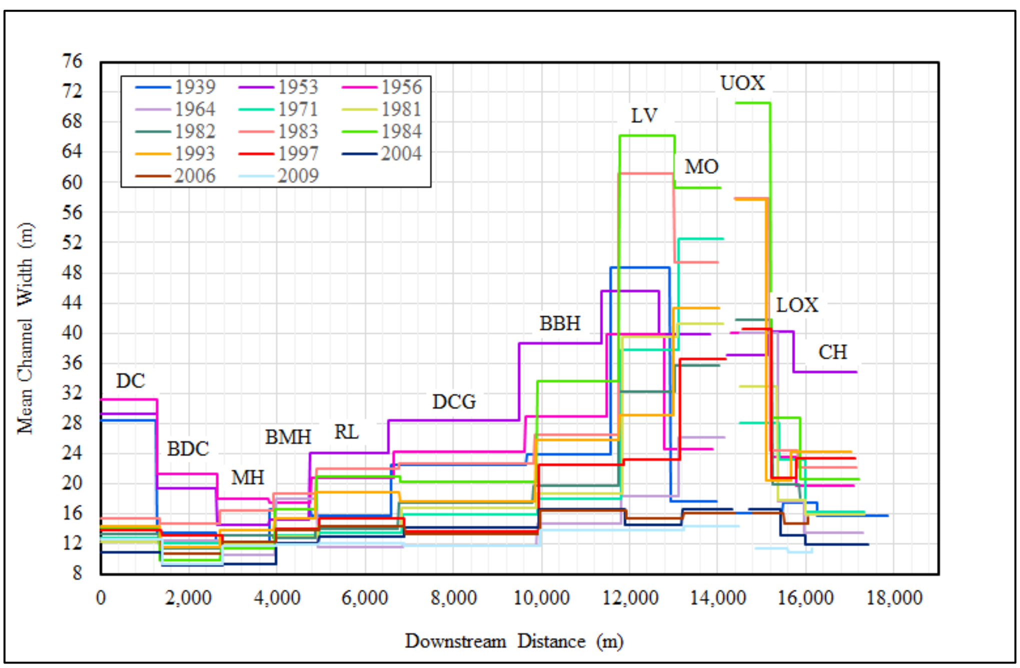

Figure 1.53. Mean channel width (m) of all 13 reaches on the LDFK for all air photo series from 1939-2009.

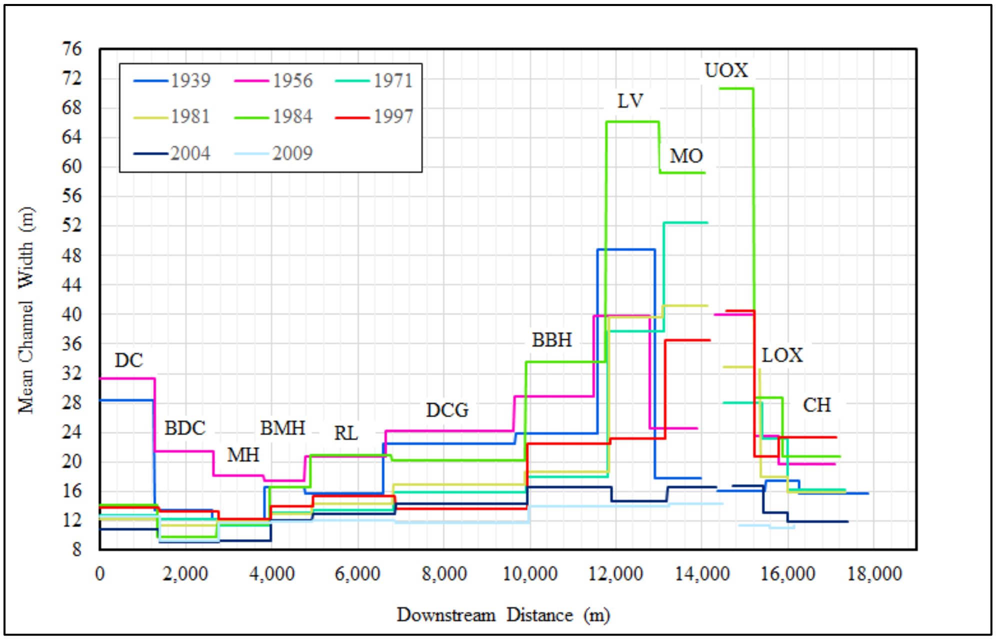

Figure 1.54. Mean channel width (m) of all 13 reaches on the LDFK for select air photo series between 1939-2009. The number of years plotted is limited to better illustrate broader patterns throughout the 20th century.

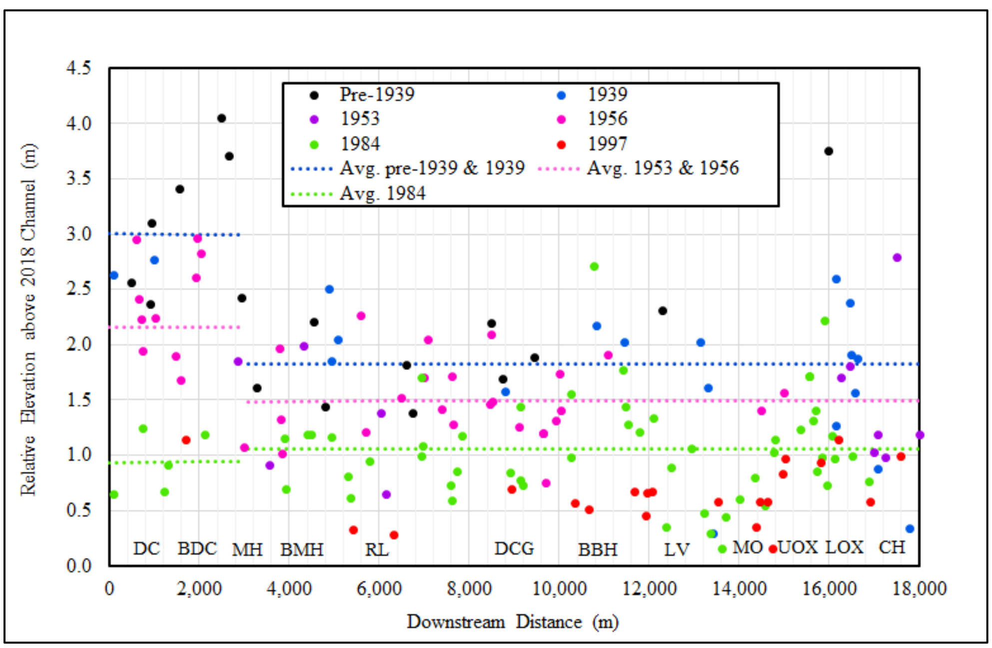

Figure 1.55. Relative elevation of relict surfaces above the modern channel (m) of all 13 reaches on the LDFK. Average elevation is shown for surfaces remaining from 1939 and before, 1953 and 1956, and 1984. Averages calculated separately for RM 0-3000 and greater than RM 3000.

elevation of relict surfaces above the modern channel again for selected years to illustrate the patterns more clearly in elevation over time and how they relate to changes in channel width. Although all mapped surfaces were identified as distinct, contiguous surfaces with little variation in elevation, it is not possible to distinguish whether the relict surfaces represent particular fluvial landforms such as floodplains, bars, or channel bed. Local variation in elevation across the active channel at any one time is of the order 1 m, suggesting comparable resolution in evaluating changes in surface (and channel) elevation from time to time and place to place.

The upper 3,000 m of LDFK appears to have aggraded more in the first years of the flow augmentation compared to the remainder of LDFK (Figure 1.55). The 1952 flood lowered the channel elevation while producing a maximum channel width (Figure 1.54, Figure 1.55). The channel narrowed by 1964 (Figure 1.53) and was considerably lower by the 1984 flood (Figure 1.55). Downstream, from RM 3,000 to RM 18,000 the slope of the river and elevations of the relict surfaces above the modern channel are relatively consistent throughout history. Some channel incision was inferred due to the 1952 and 1984 floods; however, it is a smaller amount compared to the upper 3,000 m on LDFK (Figure 1.55). During the 1983 and 1984 floods, widening occurred RM 4,000 to RM 10,000 from Below Monks Hollow to Diamond Campground while Levee to Oxbow reaches underwent extreme widening (Figure 1.53, Figure 1.54), producing a broad braid plain that has persistent throughout the project period and remains (inactive and vegetated) to the present day. After the removal of the diversion flows, mostly a meandering and single thread channel remained with vegetation along the banks.

The first 25 years of water and sediment delivery from Sixth Water Creek caused LDFK to aggrade to a higher elevation than the presumed pre-disturbance channel (Figure 1.55). We do not have aerial photography to show us what the channel looked like before 1939, however, historical alluvial surfaces exist from which we can infer bed elevations in the first decades of flow diversion. Where preserved, pre-1939 channel surfaces were on average 2.5 m to 4 m above the modern channel (Figure 1.55). In the upstream section of the LDFK (Dry Canyon through

Red Ledges) there are twelve pre-1939 relict surfaces with an average of 2.5 m above the modern channel. In the downstream section of the LDFK (Diamond Campground downstream to Childs) there are five pre-1939 relict surfaces with an average of 2.4 m above the modern channel. The fact that there was a greater concentration of pre-1939 relict surfaces on the upstream end of LDFK may reflect later removal of the early surfaces from greater lateral movement of the downstream river. Many of these relict surfaces that are of higher elevation above the modern channel are in the first 3,000 m in the Dry Canyon and Below Dry Canyon reaches (Figure 1.55). Although there is little room for sediment storage in these highly confined reaches, aggradation was most likely at a maximum in this upstream reach and a few exceptionally high surfaces remain.

The 1939 air photos reveal a meandering channel with mature riparian corridor along most of its length. The channel during this time was 12 m to 24 m wide (Figure 1.53, Figure 1.54), which is about two to three times wider than the natural channel width in the absence of flow augmentation (Jones et al., 2023). Alongstream variation in channel width was relatively small, except for two reaches where the channel was unusually wide (Figure 1.53, Figure 1.54). In Dry Canyon, a braid plain filled a portion of the reach with a wider valley bottom. At Levee, the presence of a broad braid plain in 45% of the reach produced a 44 m median channel width (Figure 1.53, Figure 1.54).

The 1952 flood widened the upstream 3,000 m portion of the LDFK by 2 m to 8 m (Figure 1.53, Figure 1.54) and left relict surfaces 2 m to 3 m above the modern channel (Figure 1.54). Thus, the average elevation of surfaces produced by the 1952 flood was lower than the pre-1939 surfaces by almost 1 m, suggesting incision during the 1952 flood. In the downstream section of the river, RM 3,000 – RM 18,000, 1952 relict surfaces were left at 1.25 m to 2.25 m above the modern channel, demonstrating that the channel also downcut in this section after the 1952 flood (Figure 1.55). A greater amount of channel incision was observed in the upstream section compared to the downstream section by about 0.5 m (Figure 1.55). More widening occurred in the downstream reaches from Motherlode to Childs with these reaches widening from 8 m to 24 m (Figure 1.53, Figure 1.54). In 1956 the Dry Canyon to Diamond Campground reaches acquired their maximum 20th century width. In the Levee to Oxbow reaches, the 1952 flood produced significant widening. The 1952 flood left the reaches from Levee and downstream wider than the upstream reaches (Figure 1.53, Figure 1.54). In the downstream reaches, channel widths were not only wider but more variable in width. Channel change was predominantly lateral and a broad braid plain began developing from RM 12,000 to RM 16,000. Extensive lateral shifting likely eliminated many earlier fluvial surfaces.

The river channel subsequently narrowed from Dry Canyon downstream to Below Brimhall Bridge, a distance of 12 km, from 1964-1982 (Figure 1.53, Figure 1.54). The channel lowered due to the 1984 flood (Figure 1.55); however, it is hard to tell whether some of this lowering occurred before the flood because there are few relict surfaces from the interflood years. Around RM 12,000 to RM 16,000 in the Levee through upper Oxbow reaches, widening or the maintenance of a wider channel was present during this period.

Little channel narrowing occurred in the first 3,000 m downstream following 1964, suggesting that the river had become relatively static and adjusted to the diversion flows (Figure 1.53, Figure 1.54). Three to four meters of widening occurred from RM 4,000 to RM 10,000 from Below Monks Hollow downstream to Diamond Campground (Figure 1.53, Figure 1.54). The Levee to Oxbow reaches underwent extreme widening during the 1983 and 1984 floods, producing a broad braid plain with little lateral variation in elevation which remains to the present day. Due to the 1984 flood, these reaches acquired their maximum 20th century width at around 60 m to 70 m (Figure 1.53, Figure 1.54). The Below Brimhall Bridge reach widened less during this time, suggesting a transition in channel behavior between the upstream and downstream portions of the LDFK. There is not a strong alongstream pattern in the relative elevation of relict surfaces produced by the 1984 flood, although elevations did lower, demonstrating a small amount of channel incision (Figure 1.55).

By 1997, narrowing was complete from Dry Canyon downstream to Diamond Campground and the channel has remained 12 m to 16 m in width in these reaches (Figure 1.53, Figure 1.54). Downstream in the Motherlode and Oxbow reaches the channel began to narrow after 1984, however some lateral cutting was still occurring in these reaches until 1997, which allowed the channel to stay at a width around 36 m to 40 m (Figure 1.48, Figure 1.53, Figure 1.54).

Between 1997 and 2004, the last 7 years of the diversion period, the channel became meandering and single thread throughout the entirety of the LDFK. The width of the channel in the downstream section decreased by a factor of two as the broad braid plain from Levee to upper Oxbow became vegetated and the channel became single thread by 1997 (Figure 1.53, Figure 1.54). No channel narrowing occurred in the upstream 3,000 m portion (Figure 1.53, Figure 1.54). Minimal lateral channel movement prevented relict surfaces from being preserved in the upstream section compared to the abundant lateral channel movement in the downstream section that produced relict surfaces from 1997 (Figure 1.55).

After the removal of the diversion flows in 2004, the lower Diamond Fork River has remained mostly a meandering single thread channel with some vegetation along the banks until the end of the study period in 2021. In the last seven years of the high flow era (1997-2004), the channel went from braiding in some sections to single thread, particularly in the lower reaches of LDFK. In the downstream section of the LDFK the single thread channel flows through a former broader braid plain. There are quite a few post-diversion relict surfaces, meaning surfaces that were abandoned after the diversion flows were removed from the river in 2004. These surfaces are typically located on the mid to downstream section of the lower Diamond Fork (Diamond Campground downstream to Motherlode) and are typically point bars about 0.5 above the modern channel.

5.2 Role of Valley Confinement

The LDFK can be divided according to the degree of confinement and valley slope: confined to partially confined (Dry Canyon downstream to Red Ledges) and largely unconfined (Diamond Campground downstream to Childs).

The upstream portion of the lower Diamond Fork River is located in a confined to partially confined valley setting and contains the reaches Dry Canyon, Below Dry Canyon, Monks Hollow, Below Monks Hollow, and Red Ledges (Figure 1.56). In this section of the river, the 1952 flood had a greater impact than the 1983/1984 floods based on observations that the earlier flood caused the channel to widen more, straightened the river, caused the river to cut down, and produced sediment deposits that were found throughout the channel in 1956. The 1952 flood produced widening and incision, leaving a coarsened channel that was more resistant to further erosion. Vegetation establishment on channel adjacent surfaces from 1952 to 1983 reduced channel width, but the coarse channel provided to be largely resistant to further incision by the 1983 and 1984 floods. There was significantly less change in the channel width, sinuosity, and channel planform in the upstream section of the LDFK compared to the downstream section, which was due to its more confined valley setting.

The downstream section of the lower Diamond Fork River is located in a largely unconfined valley setting and contains the reaches Diamond Campground, Below Brimhall, Levee, Motherlode, Upper Oxbow, Lower Oxbow, and Childs (Figure 1.56). The broader valley bottom allowed greater lateral shifting over the years and a large fraction of the lower reaches developed a broad braid plain. The greatest lateral shifting occurred through repeated avulsions in the Below Brimhall Reach. The channel avulsed four times between 1939 and 1993. Motherlode, Levee, and upper Oxbow reaches were also very dynamic in terms of planform, over the 20th century. These reaches developed a broad braid plain and the relative elevations of the relict surfaces in this reach demonstrate that there was abundant lateral motion with relatively small changes in elevation.

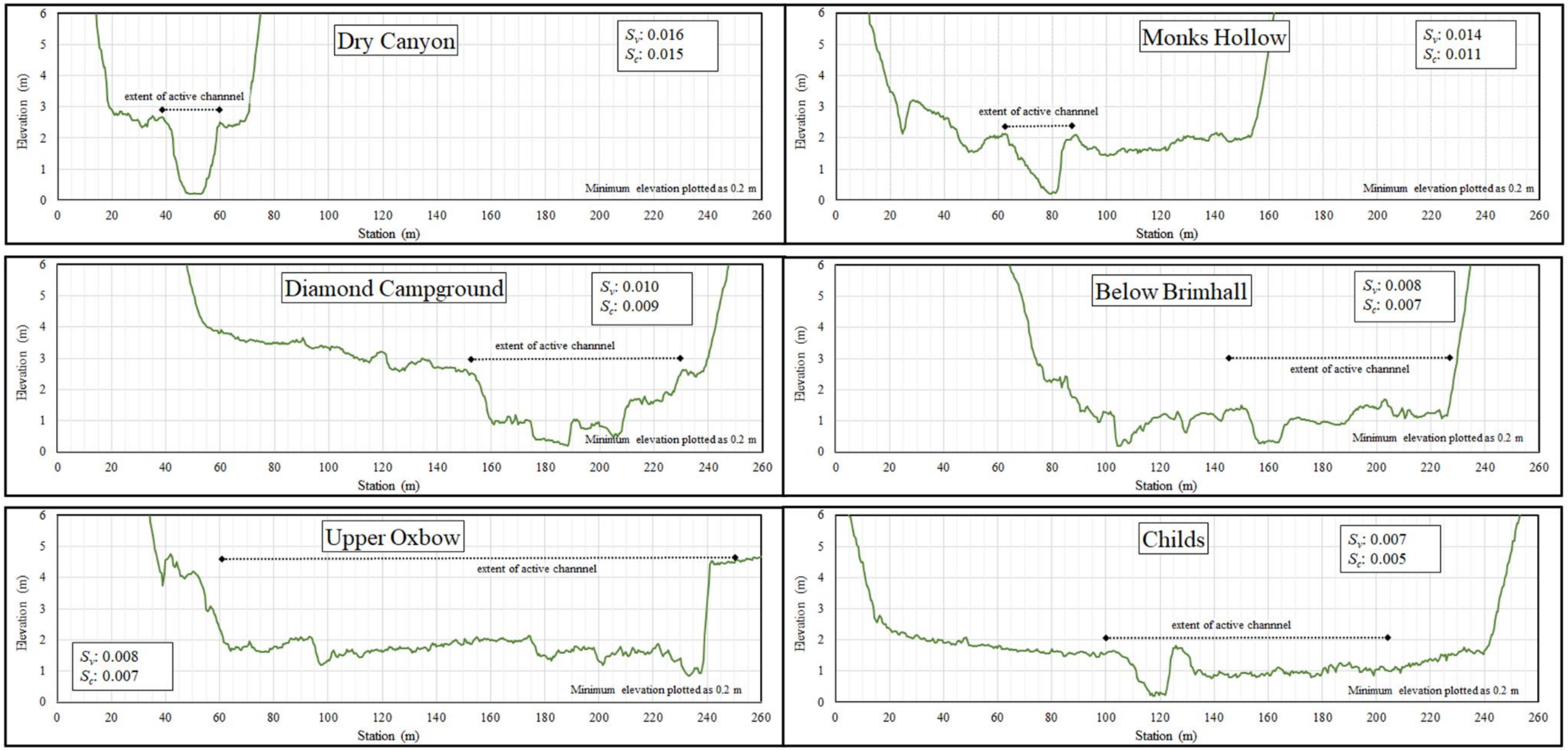

Figure 1.56. Selected cross section profiles depicting channel width going from upstream to downstream.

The 1952 flood caused greater widening than the 1984 flood in the Childs, lower Oxbow, Below Brimhall Bridge, and Diamond Campground reaches. This flood caused the most change to the Childs reach given that it caused the full meander belt of upper Childs to be occupied by unvegetated, bare sediment, and by 1956, a well-defined and nearly straight channel had developed. The channel shortened by 20% from 1939 to 1956, suggesting that the large flood, tree removal, and avulsion produced a steeper channel. The 1984 flood caused the channel to widen more than in the 1952 flood in the upper Oxbow, Motherlode, and Levee reaches. Air photos demonstrate that the 1984 flood eliminated a large amount of vegetation along the banks. All three of these reaches had developed a broad braid plain, which provided the 1984 flood the freedom to shift laterally with little sediment transport needed. After this event, subsequent narrowing was achieved through gradual vegetation of the braid plain surface.

6. Conclusion

Trans-basin flow diversions into Sixth Water Creek and lower Diamond Fork River occurred from 1916 to 2003. The large magnitude and long duration of the flow augmentation provide an opportunity to examine the river channel response to large increases in flow and sediment supply. Extensive erosion in Sixth Water Creek delivered large amounts of sediment to lower Diamond Fork in the first decades of the diversion project (Jones et al., 2023). This study examines how the channel pattern, width, and elevation of the lower Diamond Fork River responded to these changes.

Channel width and pattern were determined from air photos spanning from 1939 to 2021. Historical channel elevation was determined from surfaces abandoned by the river over the 20th century, using a 2017 Digital Elevation Model to measure the elevation of those surfaces relative to the modern river channel.

After almost 25 years of water and sediment delivery from Sixth Water Creek, the lower Diamond Fork River was generally at a higher elevation than present. The river in the early decades of the project period aggraded by at least several meters based on relict surfaces formed before 1939 that were on average 2.5 meter above the modern channel throughout the LDFK.

A large flood of 1952 caused general incision through the channel while also producing localized areas of extensive channel widening and the development of a braid plain. Meander bends were cut off by this flood and two large channel avulsions occurred. In the downstream reach of LDFK, a combination of large-scale lateral cutting with some bends growing aggressively and frequent bend cut off suggesting channel incision.

A second, even larger flood in 1984 removed vegetation along the channel, exposing the underlying gravel on the banks throughout the entire LDFK channel. Channel widening was greatest along the lowermost reaches of the LDFK, where channel adjustment tended to be lateral rather than vertical. The upstream reaches of LDFK were less impacted by the 1984 flood, presumably because incision and bed coarsening had hardened the channel and adjustment to the diversion flows was largely complete.

The lower Diamond Fork began to narrow after the major flood of 1984. Minimal channel change occurred in the upstream section of the LDFK after 1993. In the downstream reaches that had developed a broad floodplain, braiding persisted until 1997 although vegetation began to establish. Since the removal of diversion flows in 2004, the LDFK has remained mostly a meandering single thread channel until the end of the study period in 2021. The channel remains wider than comparable channels, likely due to the delivery of artificially large base flows (Jones, 2018; Stout, 2019).

Channel change over the 20th century has been smaller in the upstream portions of the lower Diamond Fork River (Dry Canyong downstream to Red Ledges) compared to the downstream reaches of the river (Diamond Campground downstream to Childs). The valley bottom in the upstream portion is considerably narrower and largely confined by bedrock, terraces, and a road embankment. Valley confinement limits lateral adjustments in the channel and the channel change observed was predominantly vertical. In contrast, the less confined lower reaches of the LDFK displayed much greater lateral adjustment than vertical over the period of flow augmentation.

CHAPTER 2

EVALUATION OF RECENT CHANNEL CHANGE TO GUIDE RESTORATION ACTIONS

1. Introduction

In 2004, flow augmentation was eliminated from the Sixth Water Creek/Diamond Fork River system. The channel has subsequently narrowed, although, the extent of narrowing may be limited by the presence of elevated base flows (Jones, 2018; Stout, 2019). There is an interest in maintaining and improving fish habitat on the lower Diamond Fork River (Figure 1.1) while also maintaining a widened channel geometry as a desired component of a recreational fishery (Wilcock et al., 2019). Previous work raises several questions regarding future instream habitat (Allred Restoration and BIO-WEST, 2018; Jones, 2018; Wilcock et al., 2019): Will narrowing continue? Will topographic complexity increase or decrease? Would direct actions such as instream structures improve the habitat? This paper contributes to that discussion by examining channel change from 2011 to 2021 with the goal of describing the patterns of channel change during this recent 11-year period. The analysis begins in 2011 to align with the largest natural flood to occur on the LDFK since the removal of flow augmentation (16 May 2011, 735 ft^3/s).

Increasing channel complexity is often a stated goal of river restoration, particularly when the management goal is to improve a fishery and aquatic ecosystem by increasing the diversity and gradients between different instream habitats (Chessman et al., 2006; Wohl et al., 2005, 2015). The return of the natural flood regime on LDFK may be a positive step for natural processes that could promote improved habitat, inasmuch as flow alteration is cited in the degradation of many fisheries (Sofi et al., 2020). The lower Diamond Fork appears to still be adjusting to 87 years of exceptionally high diversion flows and their legacy of channel change. An outstanding question regarding the current and future flow regime concerns the presence of elevated base flows mandated by the Central Utah Project Completion Act (CUPCA) that authorized construction of the pipe and tunnel system used to remove diversion flows from Sixth

Water Creek and LDFK (Allred Restoration and BIO-WEST, 2018; Stout, 2019; United States Congress, 1992; Wilcock et al., 2019).

A variety of factors can contribute to increased complexity of instream topography and substate. In-channel wood, channel shifting, and bend growth are examples of mechanisms that can increase this complexity and allow for greater spatial heterogeneity in the river corridor (Wohl et al., 2005, 2015). A greater area for the river has to shift, typically allows for a more diverse aquatic ecosystem (Wohl et al., 2022). However, a river channel can still continue to change on its own through its more recent flow regime as river ecosystems constantly respond to environmental flux and human activities (Wohl et al., 2005).

Vegetation plays an important role in promoting and maintaining channel size and pattern. Vegetation on river channel banks and on bars constricts the flow of the river through bank stabilization due to root reinforcement (Tal et al., 2004). Since bank strength is determined by the size, composition, and cohesiveness of the bank material, well-established vegetation and its root system improves soil structure and strength, which helps prevent bank erosion (Dominick, 1997; Tal et al., 2004). Mature vegetation can also be more resistant to removal by scouring and may act as a potential trap or sink for sediment producing in-channel bars (Scott et al., 1993). Plants need water and suitable soil to grow. The two work together as finer soil provides greater water holding capacity. Elevation above the channel can be a proxy for water access (Hupp and Osterkamp, 1996; Lallias-Tacon et al., 2017). The key factor that determines if a surface will become vegetated or not may be the size of the sediment and, in particular, whether the overlying sediment is fine grained. Fine grained sediment provides a more suitable growing environment and helps to retain water (Gage and Cooper, 2004). Thus, it is important to understand how vegetation along the lower Diamond Fork River recovered after the 2011 flood.

Flow augmentation was eliminated from the Diamond Fork system in 2004, leaving only base flow augmentation. The magnitude of the mandated base flows was 80 ft^3/s during the summer irrigation period (generally June – September) and 60 ft^3/s the rest of the year. Natural base flows on LDFK are generally smaller than 10 ft^3/s, raising the possibility that elevated base flows may play a role in maintaining a wider and, perhaps, simpler channel (Wilcock et al., 2019). Lower baseflows have been used since 2018 on a temporary, exploratory basis, and may play a role in channel change between 2018 and 2021.

2011 was chosen as the starting point of this study to coincide with channel disturbance associated with the spring flood of 2011. Channel adjustments toward its current pattern and size began in 1997 with the removal of diversion flows from most of Sixth Water Creek and a likely decrease in sediment supply to LDFK. With the completion of the CUPCA network and removal of large diversion flows starting in 2004, eight years of channel adjustment preceded the 2011 flood. The 2011 flood was not exceptionally large—roughly a 10-year recurrence interval—(Figure 1.3) but did produce channel widening and removal of riparian vegetation. The 2011 flood provides something of a natural starting point for examining channel recovery, including revegetation. High-resolution aerial photography from 2021 provides an end date for the study, for 11 years of channel adjustment.

Previous work found that the prescribed instream flow mandates that augment baseflows were too large and that key habitat elements, particularly pools, were lacking throughout the river (Stout, 2019). Stout (2019) documented a simplification of instream habitat and loss of deep-water features throughout the LDFK in concurrence with channel narrowing, which occurred following the implementation of minimum instream flows. The extent of narrowing was likely due to the baseflow regime, preventing establishment of vegetation and storage of sediment within the permanently wetted channel (Wilcock et al., 2019). A smaller baseflow is likely to induce further channel narrowing. A narrower channel makes floods more effective which in turn produces more sediment transport (Wilcock et al., 2019). This is a necessary component for the formation and maintenance of bars and pools (Stout, 2019). Therefore, lowering the baseflow (from 80 ft^3/s to 40 ft^3/s) will likely allow for such narrowing and provide a more suitable habitat for brown trout within the current channel (Stout, 2019).

Previous work (Allred Restoration and BIO-WEST, 2018) agreed that after the diversion flows were removed from the Diamond Fork system, many sections of the channel simplified into long, straight, deep, fast runs that lacked in-channel structure necessary for pool formation. Pools were concentrated at meander bends where they were forced by the impact of vegetation, woody debris, boulders, and bedrock. This chapter adds to the discussion of how the channel has continued to change and narrow over the 21st century and describes some of the mechanisms of change.

Therefore, the fundamental questions of this study were: How has the lower Diamond Fork River channel changed from 2011-2021? How has the LDFK recovered since the 2011 flood? Is the LDFK channel approaching a new equilibrium?

2. Methods

The goal of this study was to document channel change after the removal of the diversion flows on LDFK in 2004, specifically looking at the changes from 2011-2021. Aerial photography available for the study is at a consistently higher resolution than the early air photos used to study 20th century channel change. As a result, the methods used for evaluating recent channel change are different from those used in the previous chapter. In particular, the channel boundary was mapped based as that of the wetted channel, rather than a broader "active" channel, which includes adjacent areas free of vegetation. This approach facilitated a second mapping technique wherein we tracked the vegetation condition of channel-adjacent surfaces left free of vegetation by the 2011 flood. Although a detailed survey of riparian vegetation succession is beyond the scope of this study, tracking the fate of flood-bared surfaces contributes a useful component to describing channel change in the current regime.

2.1 Detailed Mapping Methodology

The wetted channel was mapped in ArcGIS Pro on 2011, 2014, 2016, 2018, and 2021 aerial imagery (Table 2.1). These wetted channel boundaries were used to document channel

Table 2.1. Dates and sources of available aerial imagery used for Chapter 2 including the discharge of the Diamond Fork River on the dates the imagery was taken.

Year	Source	Scale/Resolution	Color	Flight Dates(s)	Discharge at Diamond Fork Gage (ft^3/s)
2011	NAIP	1 m	Color	8/6	86
2014	NAIP	1 m	Color	8/11, 9/3	82
2016	NAIP	1 m	Color	8/2, 8/19	46
2018	NAIP	0.6 m	Color	9/11, 9/26, 9/27	60
2018	Google	15 cm	Color	9/10	56.4
2021	Hexagon	15 cm	Color	9/23	40.6

pattern and width. Bare surfaces adjacent to the wetted channel were not included in the channel boundaries. In general, these surfaces were not occupied by the river again. Some became vegetated over the period 2011-2021, others did not. The channel centerline, width, and the amount of channel centerline shift between each photo pair was found using the Planform Statistics Toolbox in ArcGIS (Lauer, 2006). Sections of the 2018 aerial imagery and the entire 2021 aerial imagery datasets were found to be much higher resolution compared to the 2011-2016 aerial imagery, which allowed us to observe useful detail at the scale of sediment bars and wood jams.

Although the air photos used are of excellent quality and high resolution, there are limits to the accuracy of the channel mapping. Growth of grasses and shrubs along the channel banks can obscure the exact boundary of the wetted channel, such that small changes in channel position or width can be uncertain. Further, the discharge at the time each photograph is taken is different, providing a possible apparent shift in channel bankline due to a difference in flow depth in the channel. The magnitude of the river discharge for each air photo is given in Table 2.1 and the possible influence of discharge on apparent width and channel shift will be noticed as needed below.

2.2 2011 Bare Spot Analysis Methodology

The flows of the 2011 flood scoured vegetation and fine sediment cover along the banks, causing the exposure of underlying gravel. This presented the opportunity to evaluate which surfaces subsequently revegetated and the role of revegetation in channel change. Bare surfaces were delineated on the 2011 photographs and those locations were then examined on the 2018 air photos to determine whether the bare spots had become revegetated (Table 2.1). The 2018 photographs were used because they are closest in time to the 2017 LiDAR DEM, allowing determination of the elevation of the surfaces relative to the 2017 channel. This LiDAR topography flown October 3-6, 2017 by the National Center for Airborne Laser Mapping (Jones, 2018).

Bare surfaces visible in the 2011 imagery were classified in 2018 as bare, partly vegetated, vegetated, or water (integrated into the wetted channel) (Figure 2.1, Figure 2.2). Surfaces classified as vegetated contained roughly 80%-100% vegetation, partly vegetated if they

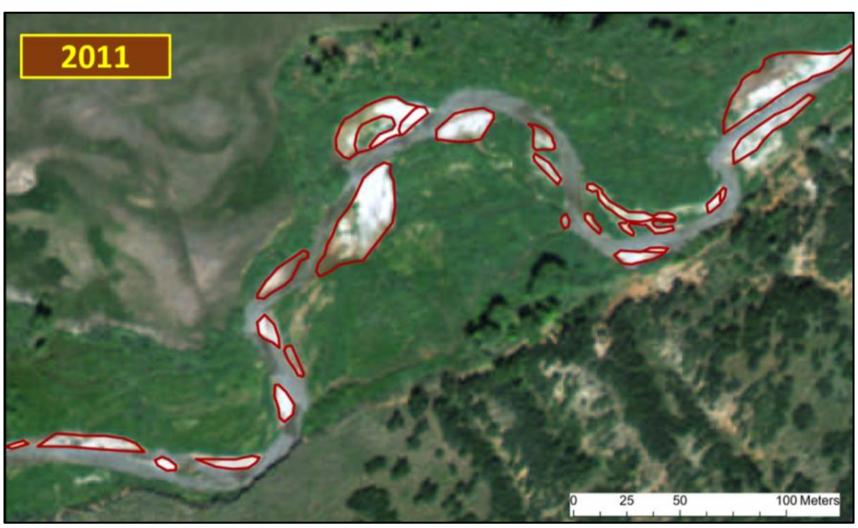

Figure 2.1. Example of delineated surfaces that became unvegetated due to the 2011 flood on 2011 NAIP imagery.

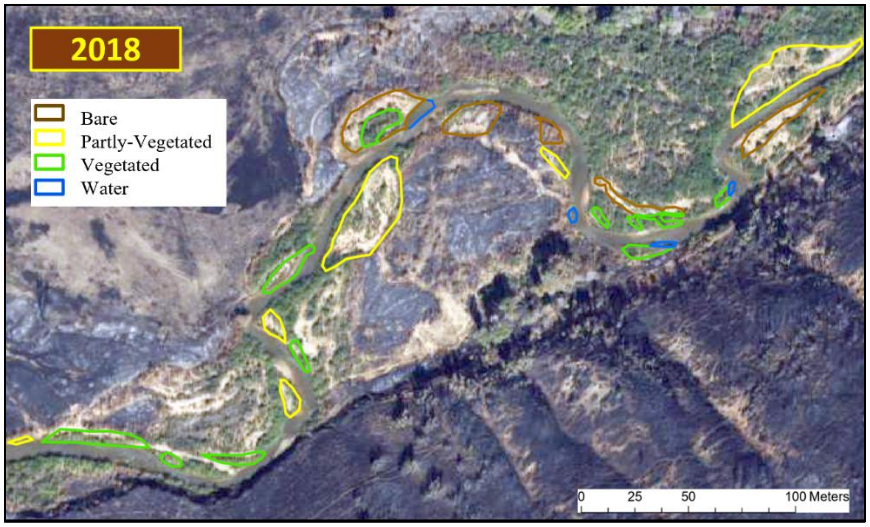

Figure 2.2. Example of what became of the delineated 2011 unvegetated surfaces on 2018 NAIP imagery. The color of the polygons represents their vegetation classification in 2018.

contained roughly 20%-80% vegetation, and bare if no vegetation was present. No attempt was made to describe their vegetation type, but willow is the dominant shrub growing in the near-channel bare spots. The 2018 imagery was taken after the Pole Creek fire that sparked on September 6, 2018, and passed through the Lower Diamond Fork area from September 15 - 18, 2018.

A topographic analysis was conducted using ArcGIS Pro to find the elevation of these mapped surfaces relative to the 2018 wetted channel. The median elevations were calculated for each polygon to represent the range of elevations within each specific polygon.

A field visit on June 1, 2022, was completed to evaluate the mapping accuracy and conditions for vegetation establishment. Twenty surfaces were visited: six classified as bare in 2018, six classified as partly-vegetated in 2018, and eight classified as vegetated surfaces in 2018. Observations on grain size, vegetation status, and presence or absence of a fine mantle were noted. Three holes were dug about 4-5 feet apart on each surface to determine the average depth of the fine mantle of that surface.

3. Results

The primary results of this study describe the changes in channel width and pattern of LDFK from 2011-2021. This study relies heavily on visual interpretation of historical aerial images, and therefore there is room for error and bias in these interpretations.

Four main channel change mechanisms were found on the lower Diamond Fork from 2011-2021. The first was bend growth via point bar deposition and outer bank erosion. Typically, this narrowed and elongated channel bends. The second was bar deposition not in bends, where sediment was deposited in the channel creating a bar, therefore narrowing the channel. The third mechanism was bar cutting and bar deposition. This occurred when the wetted channel cut through a bar on one side of the river to then deposit another bar on the opposite side of the river. This caused the river to shift from one side to the other of the broader active channel. The fourth channel change mechanism occurred where wood accumulated in the channel, forcing a backwater and a change in the dominant flow path, causing a channel shift or a local avulsion.

3.1 Dry Canyon (Reach 1)

The LDFK in the 1.4 km Dry Canyon reach has a 1.5% slope and is largely confined between bedrock walls and further constrained by the Diamond Fork Forest Road. The riverbed is coarse gravel/cobble with little storage of mobile sediment in the present regime.

Very little channel change occurred in the Dry Canyon reach from 2011-2021 due to its confined valley setting and coarse, armored bed (Figure 2.3). A small amount of channel narrowing occurred in some wider sections (Figure 2.4) caused by bar deposition along the banks. Minimal channel shifting occurred throughout this reach (Figure 2.5), however, small amounts of apparent channel shifting may result from uncertainty in delineating the wetted channel where shadows obscure the banks. Larger channel shifts from 2014-2016 were most likely due to new bar deposits inside the channel, although in these photos, shadows obscure the banks which provide uncertainty in the delineation of the 2014 and 2016 wetted channels in this reach.

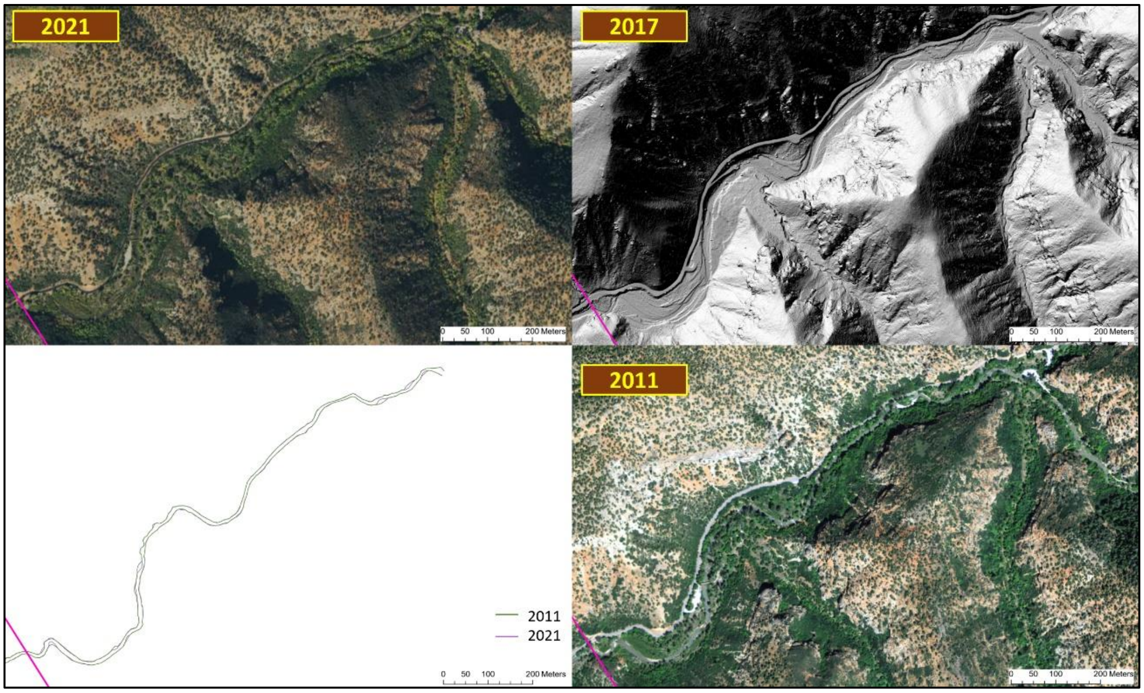

Figure 2.3. Dry Canyon reach in 2011, 2017, and 2021 and the bank lines of the 2011 and 2021 active channels.

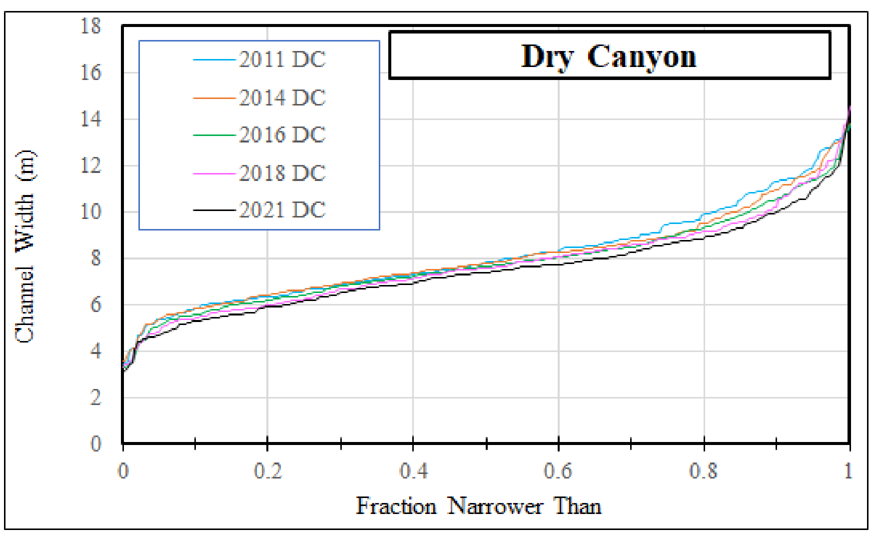

Figure 2.4. Cumulative distribution of channel width (m), 2011-2021, for the Dry Canyon reach.

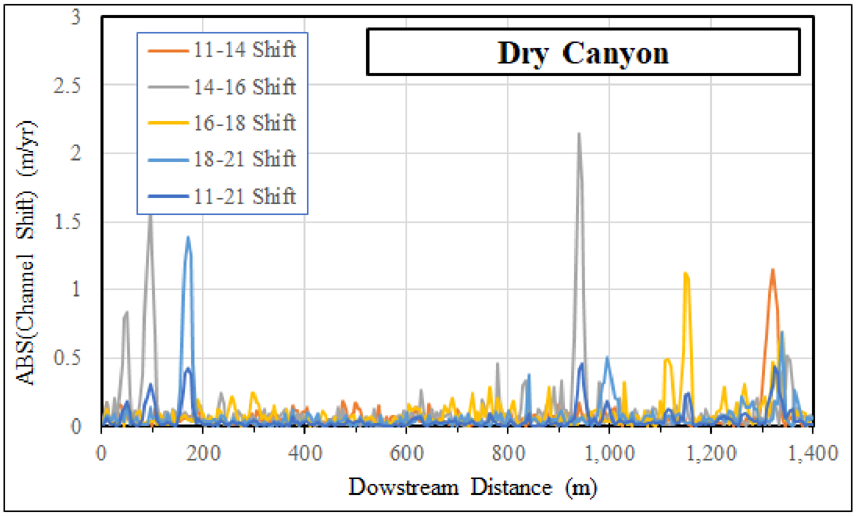

Figure 2.5. Downstream distance (m) vs. the absolute value of the amount of channel centerline shift (m/yr) from 2011-2021 for the Dry Canyon reach.

Channel shifting from 2018-2021 around RM 170 was due to a new bar deposit in 2021 (Figure 2.5).

One localized instance of channel change occurred at a bend located at the downstream end of this reach around RM 1,300. This bend narrowed from 2011-2016 due to point bar deposition in 2014 with the point bar continuing to grow until 2016. This section of the channel narrowed from 2016-2018 due to a small bar deposit, then widened from 2018 to 2021 back to the width it was in 2016. A wood jam at the location in 2021 increased the wetted channel via flooding and led the channel to shift slightly (Figure 2.5).

The 2011 flood produced few unvegetated locations in this coarse, steep, and largely static reach. Five surfaces remained bare seven years later, one surface became partly vegetated, one became more fully vegetated, and one was integrated into the wetted channel. Most of the surfaces were no more than about 0.6 m above the 2017 channel (Figure 2.6). All of these surfaces were located on the inside of bends.

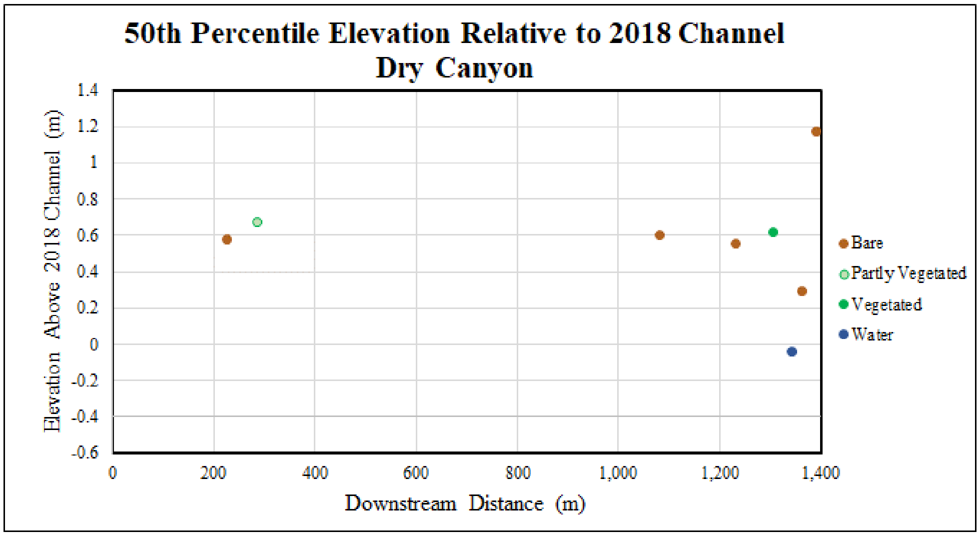

Figure 2.6. 50th percentile elevation relative to the 2018 channel of the unvegetated surfaces from the 2011 flood and their vegetation classification in 2018 for the Dry Canyon reach.

3.2 Below Dry Canyon (Reach 2)

The LDFK in the 1.4 km Below Dry Canyon reach has a 1.5% slope, is largely confined between bedrock walls, and further constrained by the Diamond Fork Forest Road and bank protection associated with USFS group campsites. The riverbed is coarse gravel/cobble with little storage of mobile sediment in the present regime.

Very little channel change occurred throughout the Below Dry Canyon reach from 2011-2021 as this reach is located in a confined valley setting with a coarse, armored bed (Figure 2.7). Because of this, there was little to no channel narrowing and channel shifting (Figure 2.8, Figure 2.9). One short reach became slightly wider from 2016-2018, due to bank erosion on river right and deposition on river left. Based on the minimal channel change that occurred in this reach and due to its confined valley setting, it is likely that there will be very little channel change in the future.

Only three unvegetated, or bare surfaces were left by the 2011 flood. The surfaces are all approximately 0.6 m above the modern channel and one each remained bare, became partly

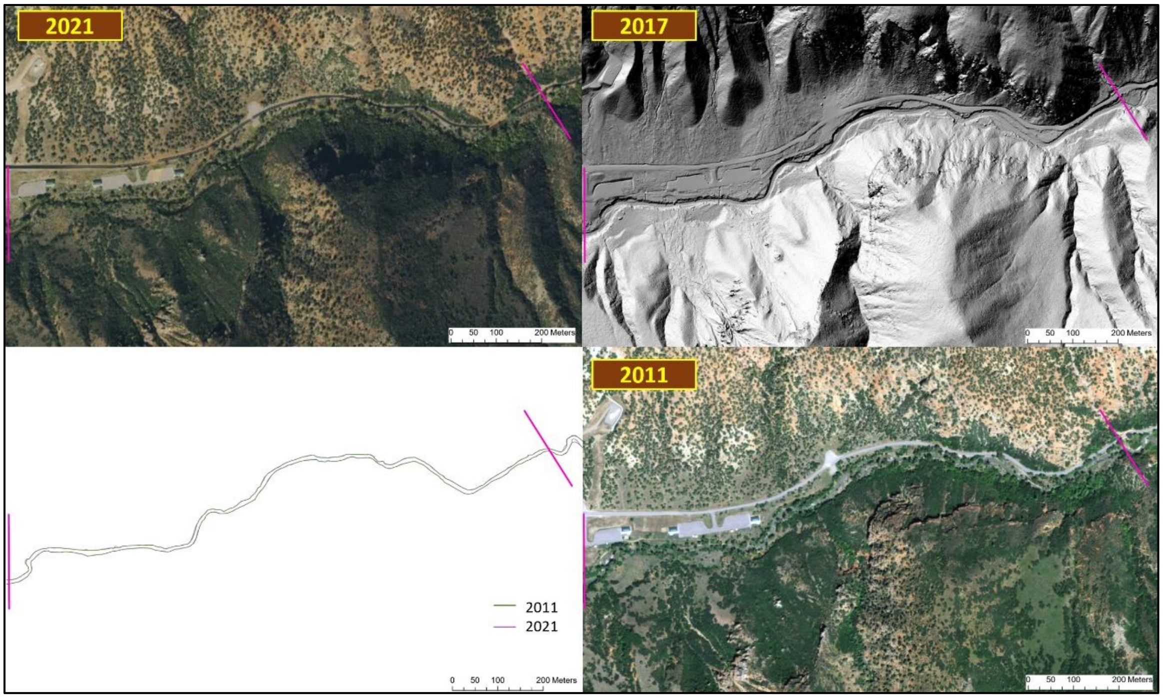

Figure 2.7. Below Dry Canyon reach in 2011, 2017, and 2021 and the bank lines of the 2011 and 2021 active channels.

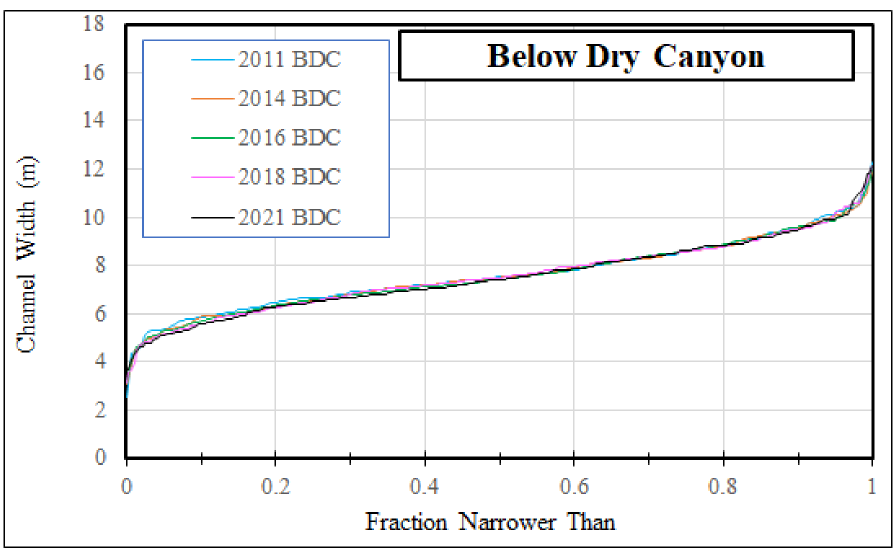

Figure 2.8. Cumulative distribution of channel width (m), 2011-2021, for the Below Dry Canyon reach.

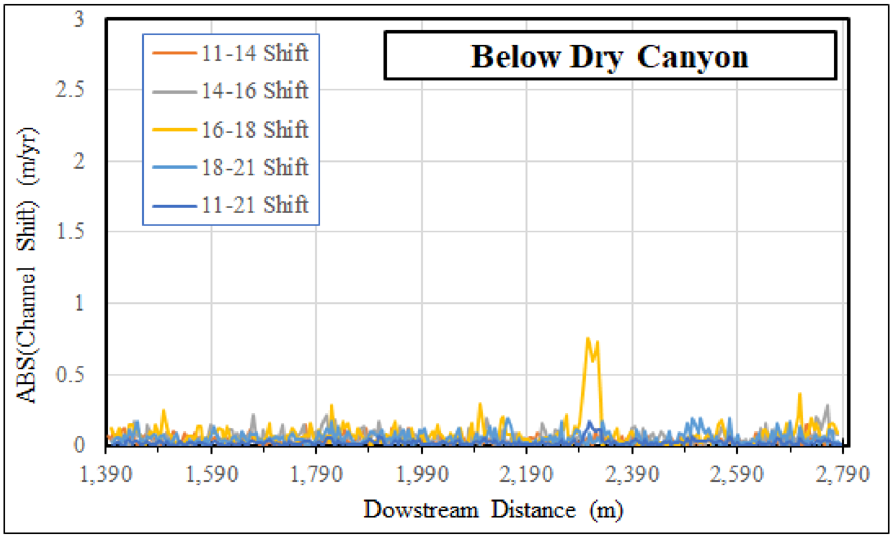

Figure 2.9. Downstream distance (m) vs. the absolute value of the amount of channel centerline shift (m/yr) from 2011-2021 for the Below Dry Canyon reach.

vegetated, or became vegetated (Figure 2.10). All of these surfaces were located inside channel bends thus providing no apparent difference in the surfaces.

3.3 Monks Hollow (Reach 3)

The LDFK in the 1.2 km Monks Hollow reach is less steep than the upstream reaches with a 1.1% slope, is largely confined by alluvial fans and confining bedrock. This reach is further constrained by the Diamond Fork Forest Road and bank protection associated with USFS group campsites. The stream gage USGS 10149400 DIAMOND FORK ABV RED HOLLOW, NEAR THISTLE, UT is located immediately below the Monks Hollow Outlet in the downstream section of this reach. The riverbed is coarse gravel/cobble with little storage of mobile sediment in the present regime.

Minimal channel change occurred through most of the Monks Hollow reach from 2011-2021 due to its largely confined valley setting (Figure 2.11). Minimal channel narrowing was observed from 2011-2021 (Figure 2.12).

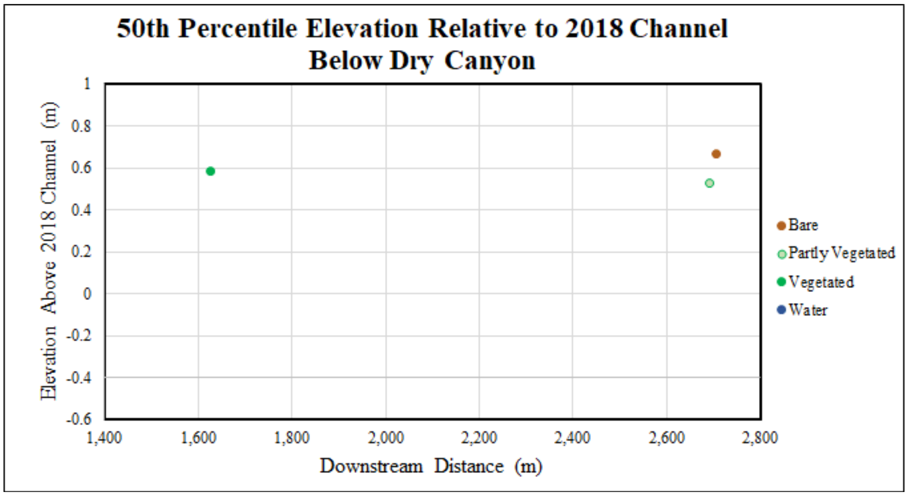

Figure 2.10. 50th percentile elevation relative to the 2018 channel of the unvegetated surfaces from the 2011 flood and their vegetation classification in 2018 for the Below Dry Canyon reach.

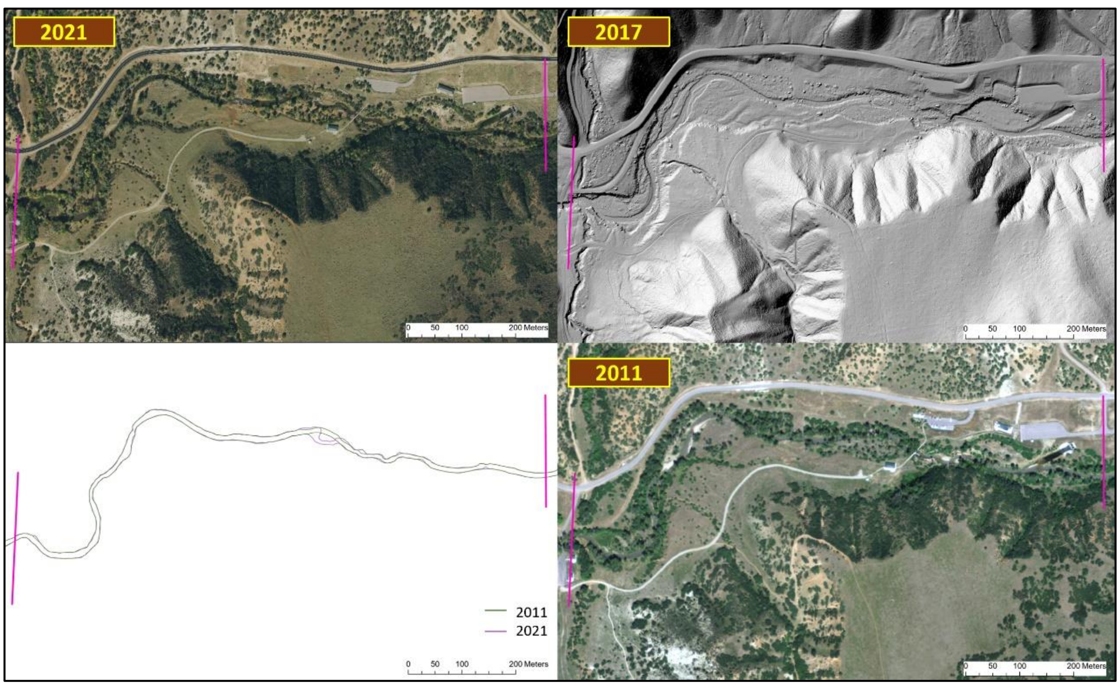

Figure 2.11. Monks Hollow reach in 2011, 2017, and 2021 and the bank lines of the 2011 and 2021 active channels.

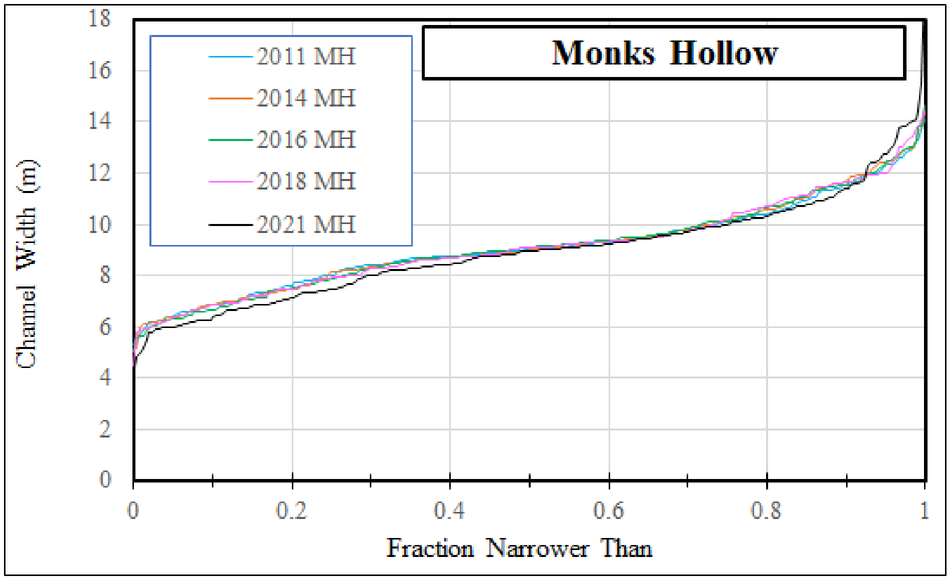

Figure 2.12. Cumulative distribution of channel width (m), 2011-2021, for the Monks Hollow reach.

Channel change occurred from 2016-2018 due to a large wood jam about 300 meters downstream of the Monks Hollow Outlet. The jam caused a backwater extending approximately 60 meters upstream, driving a local avulsion of the channel to the left. The wood jam caused the channel to shift 9.2 m/yr for 2016-2018 and a further shift of 2 m/yr for 2018-2021 (Figure 2.13). This is by far the largest wood jam observed anywhere on LDFK during the study period and the jam was sufficient to withstand all high flows from 2016 on.

The 2011 flood left 11 bare surfaces. Two lower surfaces were incorporated into the wetted channel, and one was partly vegetated. The remaining eight, with the majority around 0.6 m above the channel, remained unvegetated (Figure 2.14). One bare surface at 1.3 m above the modern channel was located on the edge of a terrace causing it to be of higher elevation compared to the other surfaces (Figure 2.14). A partly vegetated surface was found at the location where water from the Monks Hollow Outlet enters the LDFK. There was no apparent difference in the surfaces provided that all of these surfaces were located inside channel bends or next to bends.

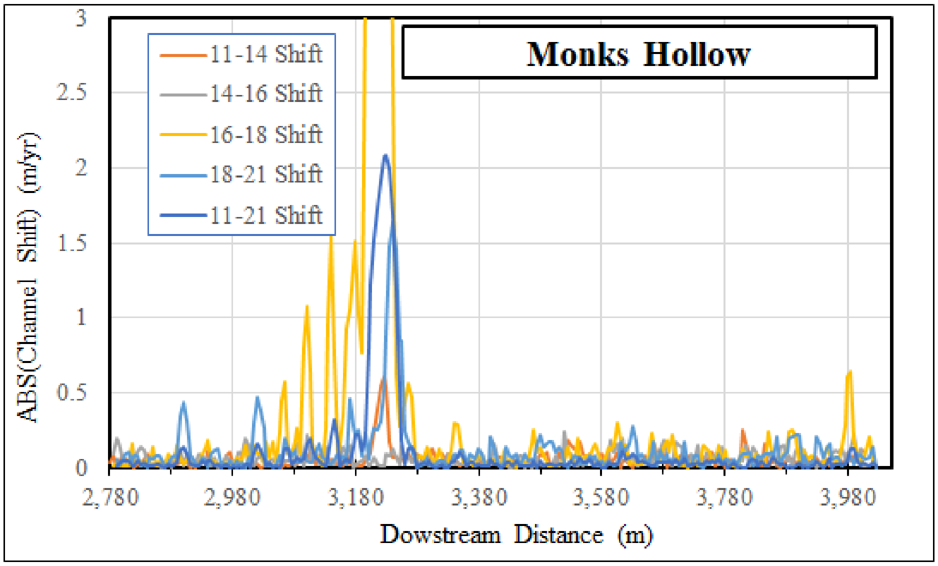

Figure 2.13. Downstream distance (m) vs. the absolute value of the amount of channel centerline shift (m/yr) from 2011-2021 for the Monks Hollow reach.

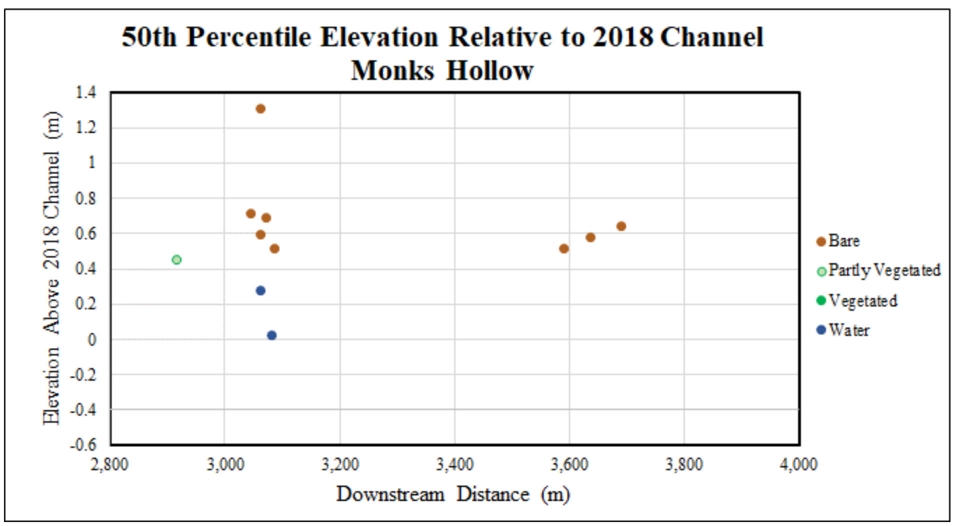

Figure 2.14. 50th percentile elevation relative to the 2018 channel of the unvegetated surfaces from the 2011 flood and their vegetation classification in 2018 for the Monks Hollow reach.

3.4 Below Monks Hollow (Reach 4)

The LDFK in the 0.95 km Below Monks Hollow reach has 1.3% slope, is largely confined by alluvial fans and an anticline that influences confining bedrock. This reach is further constrained by the Diamond Fork Forest Road. The riverbed is coarse gravel/cobble with little storage of mobile sediment in the present regime.

Very little channel narrowing and shifting occurred throughout the Below Monks Hollow reach due to its confined valley setting (Figure 2.15) and coarse, armored bed. Some channel narrowing and shifting is apparent for 2014-2016 (Figure 2.16, Figure 2.17), however this is likely due to a change in river discharge for the 2014 and 2016 imagery (Table 2.1). This is especially noticed around RM 4,100 where an apparent shift in opposite directions occurred from 2014-2016 and 2016-2018. Bar deposition from 2016-2018 was the caused more channel shifting at RM 4,100 m (Figure 2.17).

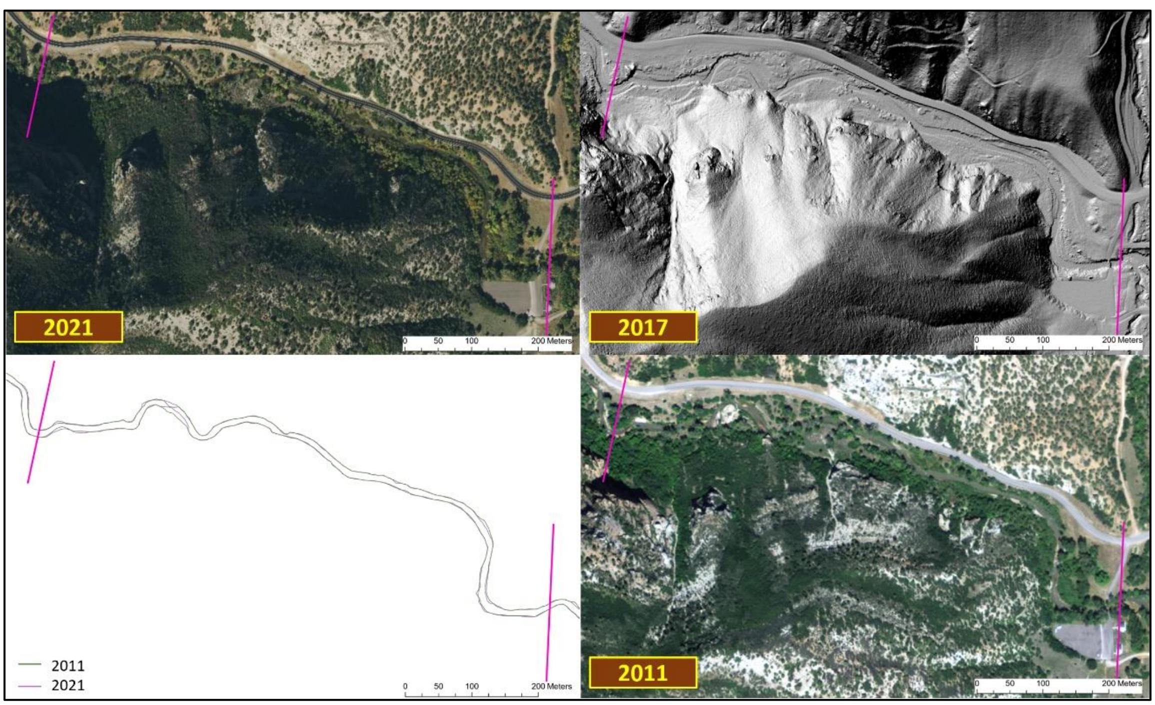

Figure 2.15. Below Monks Hollow reach in 2011, 2017, and 2021 and the bank lines of the 2011 and 2021 active channels.

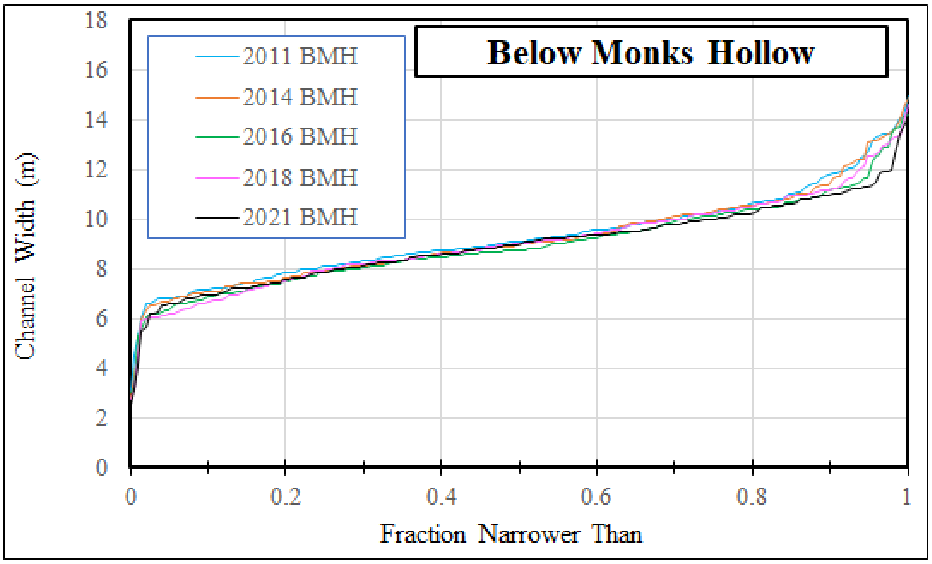

Figure 2.16. Cumulative distribution of channel width (m), 2011-2021, for the Below Monks Hollow reach.

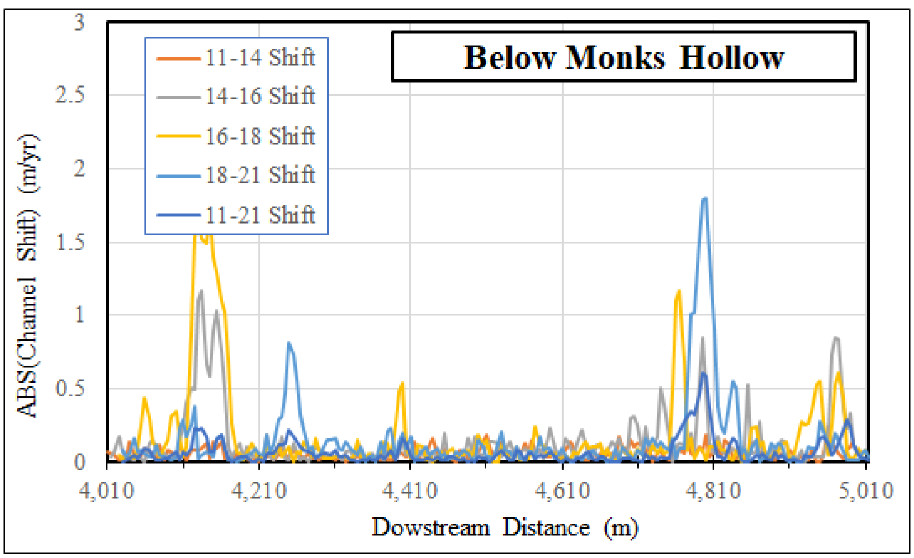

Figure 2.17. Downstream distance (m) vs. the absolute value of the amount of channel centerline shift (m/yr) from 2011-2021 for the Below Monks Hollow reach.

One bend at about RM 4,800 shifted (Figure 2.17) due to point bar deposition and outer bank erosion from 2018-2021 making the bend more elongated (Figure 2.18). Because of the valley setting of this reach, this relatively small change was the largest observed in the reach.

The 2011 flood left 11 bare surfaces. One became partly vegetated and three became vegetated (Figure 2.19). The remaining seven surfaces with the majority around 0.6 m above the modern channel remained unvegetated. The vegetated surfaces, all located in the upstream section of the reach, were also around 0.6 m above the modern channel and the partly vegetated surface was 0.3 m in elevation. There was no apparent difference among the surfaces, all of which were located inside channel bends.

Figure 2.18. Point bar deposition and outer bank erosion in Below Monks Hollow reach at RM 4,800.

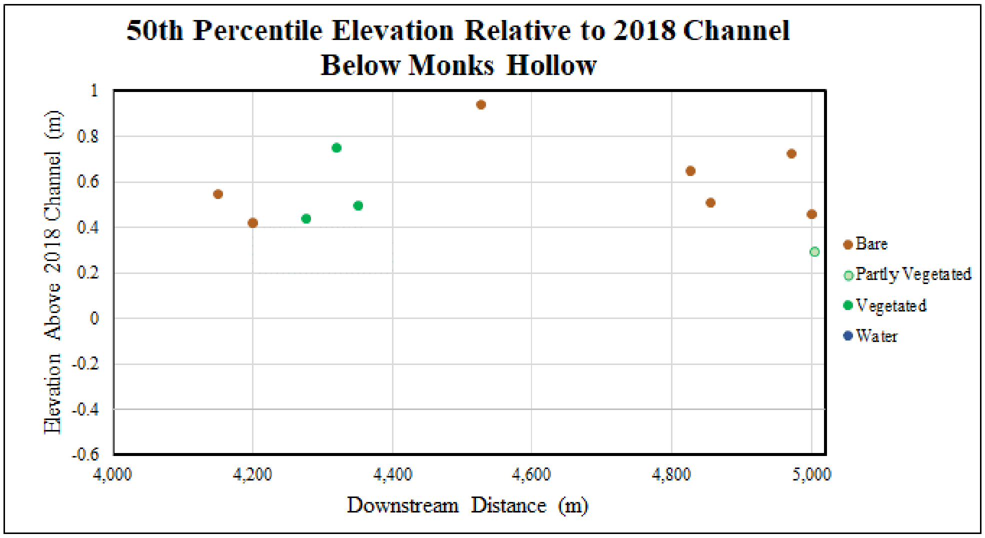

Figure 2.19. 50th percentile elevation relative to the 2018 channel of the unvegetated surfaces from the 2011 flood and their vegetation classification in 2018 for the Below Monks Hollow reach.

3.5 Red Ledges (Reach 5)

The LDFK in the 2.0 km Red Ledges reach has a 1.0% slope, is largely confined by alluvial fans and an anticline that influences confining bedrock. This reach is further constrained by the Forest Road. The historic gage USGS 10149500 DIAMOND FORK BELOW RED HOLLOW, NEAR THISTLE, UT is located in the middle of this reach. The riverbed is gravel and cobble with little storage of mobile sediment in the present regime.

Red Ledges is the most downstream reach located in a confined valley setting (Figure 2.20). Between 2011 and 2021, this reach had slightly more channel change compared to the upstream reaches, but less than the downstream reaches. There were a few sections throughout this reach where the channel narrowed very slightly between 2011 and 2014 (Figure 2.21). Abundant minor channel shifting due to bank erosion occurred in the upper half of the reach from 2014-2016 (Figure 2.22). This channel shifting was due to bank erosion. A small amount of channel shifting in three locations occurred from 2018-2021 (Figure 2.22) from point bar deposition and outer bank erosion.

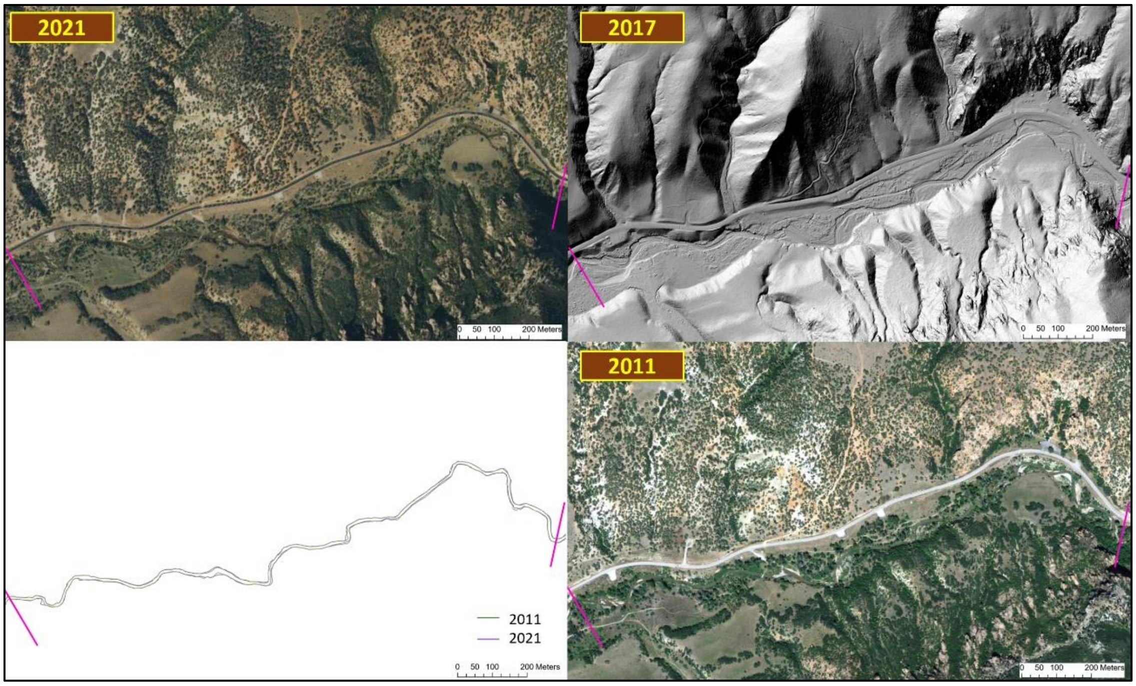

Figure 2.20. Red Ledges reach in 2011, 2017, and 2021 as well as the bank lines of the 2011 and 2021 active channels.

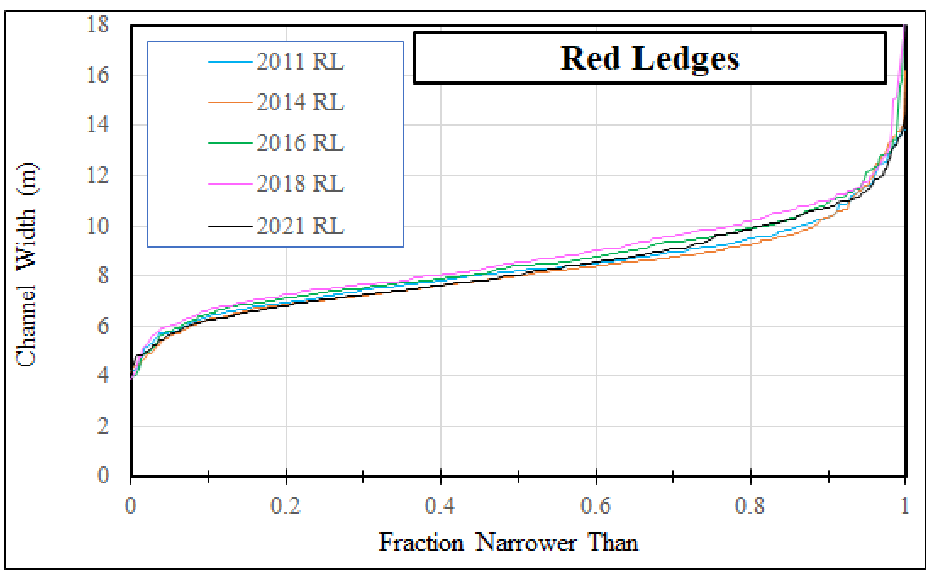

Figure 2.21. Cumulative distribution of channel width (m), 2011-2021, for the Red Ledges reach.

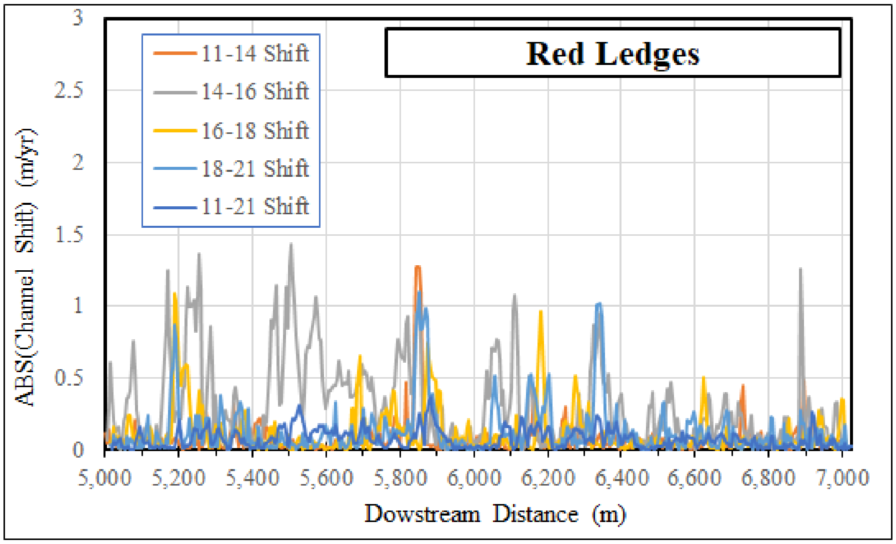

Figure 2.22. Downstream distance (m) vs. the absolute value of the amount of channel centerline shift (m/yr) from 2011-2021 for the Red Ledges reach.

The channel widened just over a half a meter from 2014-2018 due to bank erosion with the channel then narrowing about a half a meter from 2018-2021 (Figure 2.21). This channel narrowing was due to bar deposition in 2021, with some of these bars observed to be vegetated during that same year.

The 2011 flood left 26 bare surfaces. Five surfaces, mostly at lower elevation, were incorporated into the wetted channel. Four surfaces were partly vegetated with no apparent pattern in their relative elevation to the modern channel. Six surfaces, located largely in the downstream half of the reach, were vegetated and mainly around 0.2 m to 0.6 m relative elevation. The remaining eleven surfaces, around 0.5 m above the modern channel, remained unvegetated (Figure 2.23). There was no strong pattern in relative elevation above the modern channel and no apparent difference in the location of the bare surfaces. The majority of these 2011 bare surfaces were located inside channel bends.

3.6 Diamond Campground (Reach 6)

The LDFK in the 3.1 km Diamond Campground reach is the longest reach on the LDFK and flanked along most of its length by a USFS campground. This reach has a 0.9% slope and is

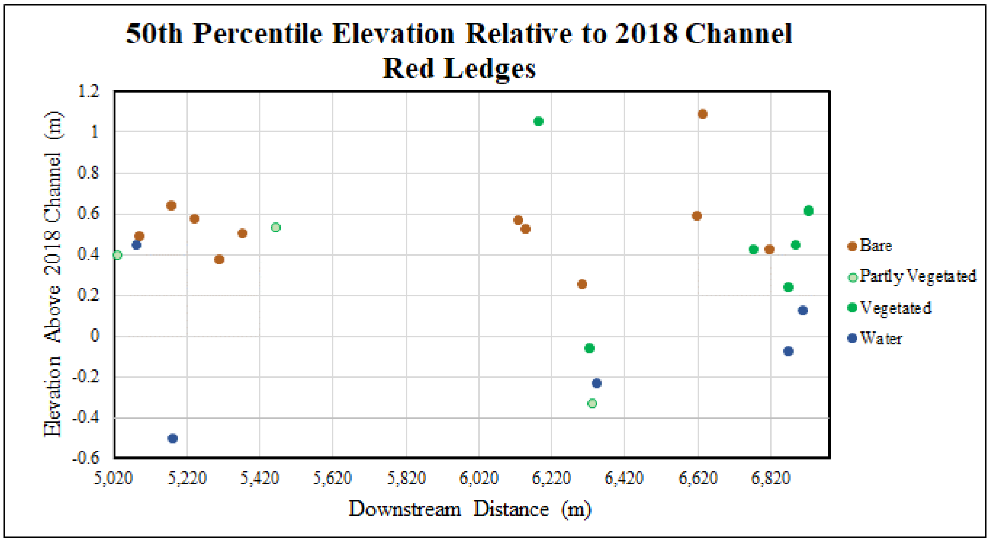

Figure 2.23. 50th percentile elevation relative to the 2018 channel of the unvegetated surfaces from the 2011 flood and their vegetation classification in 2018 for the Red Ledges reach.

largely unconfined but constrained by the Diamond Fork Forest Road and a terrace hillslope. The riverbed is coarse gravel with some storage of mobile sediment in the present regime.

The less confined valley setting allows for more lateral channel change to occur compared to the upstream reaches (Figure 2.24). The channel widened in 2018 by three-quarters of a meter to around 9.5 m and then narrowed another meter to 8.5 m in 2021 (Figure 2.25). Some of this channel widening could be due to mapping error provided that the widening was reversed back to the 2016 channel width. More vegetation was present next to the 2021 channel compared to the 2018 channel, which influenced some channel narrowing in 2021. There was consistent channel shifting from 2014-2016 (Figure 2.26) due to bank erosion throughout this reach. The channel shifting that occurred from 2016-2018 (Figure 2.26) was mainly due to point bar deposition and outer bank erosion.

Little channel shifting occurred from 2011-2016. Elongation of a couple of bends in the upper portion of the reach included point bar deposition in 2018 and 2021. The downstream portion of the reach, below RM 9,000, has larger bends both in the valley and the channel and

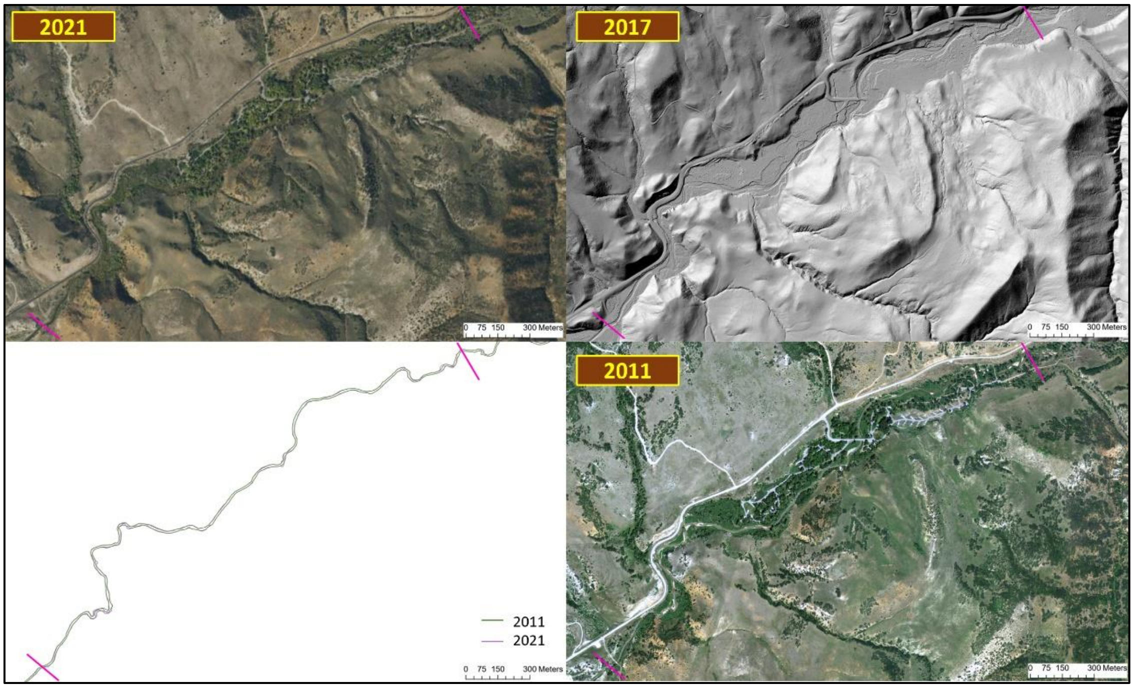

Figure 2.24. Diamond Campground reach in 2011, 2017, and 2021 and the bank lines of the 2011 and 2021 active channels.

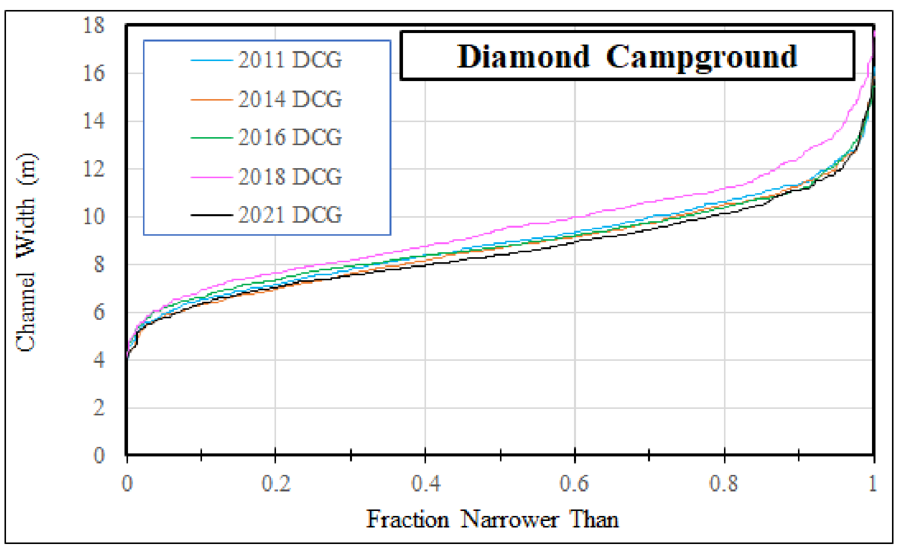

Figure 2.25. Cumulative distribution of channel width (m), 2011-2021, for the Diamond Campground reach.

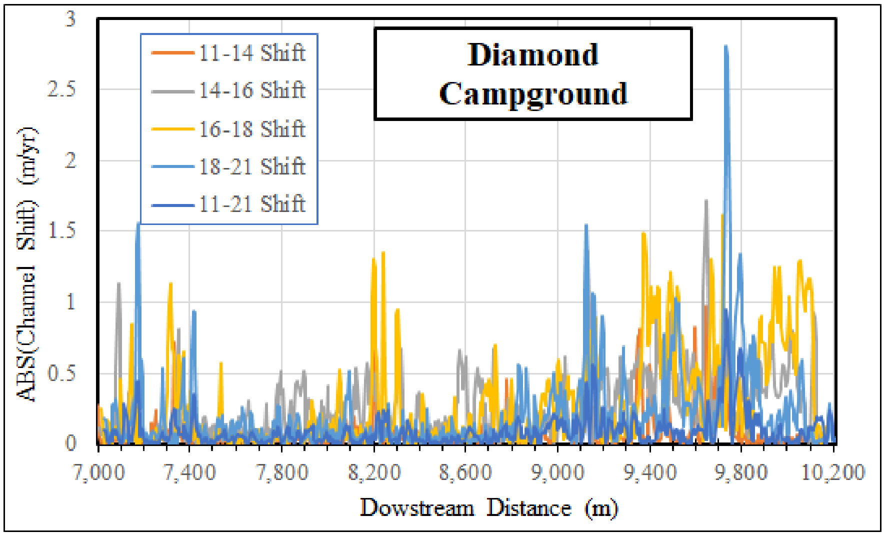

Figure 2.26. Downstream distance (m) vs. the absolute value of the amount of channel centerline shift (m/yr) from 2011-2021 for the Diamond Campground reach.

experienced channel shifting from 2016-2021 due primarily to point bar deposition and outer bank erosion (Figure 2.26).

The 2011 flood left 40 bare surfaces, almost all between 0.3 m and 0.6 m elevation (Figure 2.27). Most of these surfaces remained bare or became partly vegetated. There were only two vegetated surfaces with one very close to river level. There was no strong pattern in relative elevation above the modern channel and no apparent difference in the location of the bare surfaces provided that all of these surfaces were located inside channel bends or next to channel bends.

3.7 Below Brimhall Bridge (Reach 7)

The LDFK in the 2.0 km Below Brimhall Bridge reach had a 0.7% slope and is mostly unconfined (Figure 2.28). This reach contains the location of the historic gage USGS 10150000 DIAMOND FORK NEAR THISTLE, UTAH that is just upstream of the 1984 levee. The riverbed is coarse gravel with some mobile sediment in the present regime.

Between 2011 and 2021, the LDFK channel in this reach narrowed a total of 2.0 m (Figure 2.29). The narrowing appears to have occurred in two steps, from 2011-2014 and from

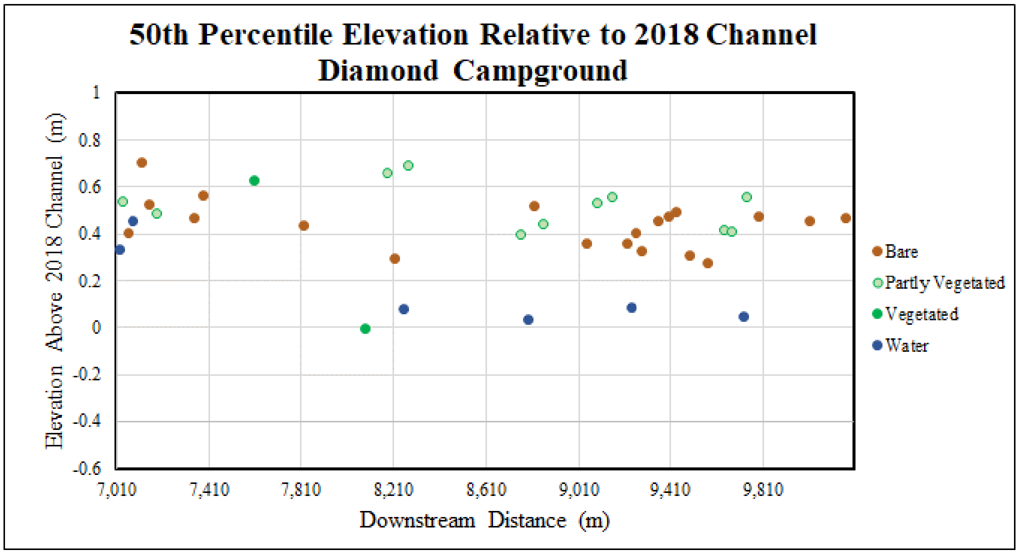

Figure 2.27. 50th percentile elevation relative to the 2018 channel of the unvegetated surfaces from the 2011 flood and their vegetation classification in 2018 for the Diamond Campground reach.

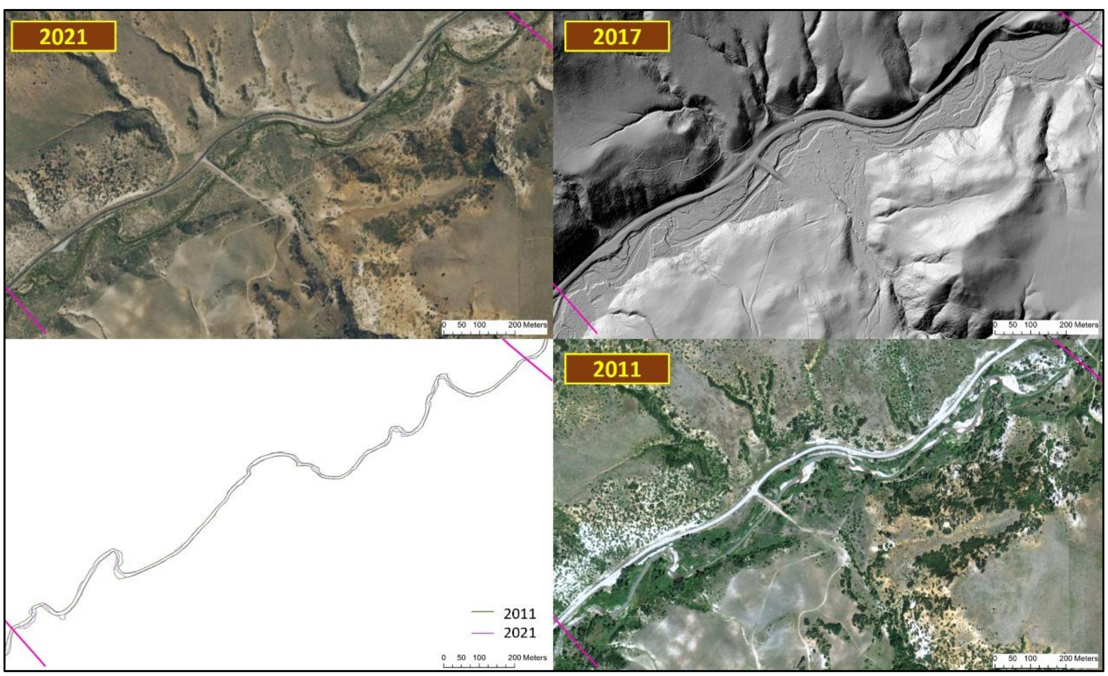

Figure 2.28. Below Brimhall Bridge reach in 2011, 2017, and 2021 and the bank lines of the 2011 and 2021 active channels.

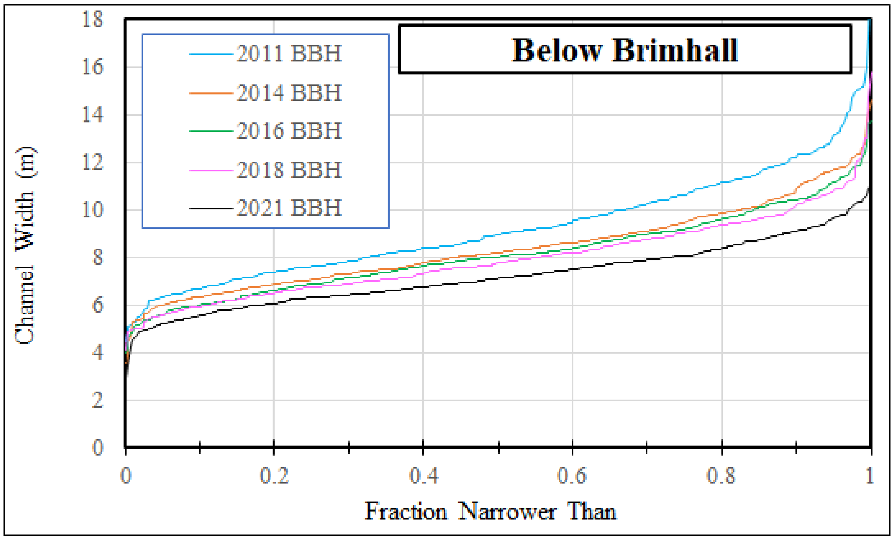

Figure 2.29. Cumulative distribution of channel width (m), 2011-2021, for the Below Brimhall reach.

2018-2021 (Figure 2.29). Bar deposition caused the channel to narrow from 2011-2014. Channel narrowing in this reach was only observed in channel bends and never in the straight sections of this reach.

Three bends (RM 10,450 m, RM 10,700 m, RM 12,100 m) in this reach became narrower and more elongated from 2011-2014 due to point bar deposition as well as some bar deposition on the outside of the bends. All point bars had become vegetated by 2016. The same three bends continued to elongate from 2016-2021 through point bar deposition and outer bank erosion, producing some channel shifting. The largest peak in channel shift from 2016-2018 was 3.5 m/yr caused by point bar deposition and outer bank erosion. Some channel shifting was observed in 2021, again at the bends mentioned before, and was caused by outer bank erosion (Figure 2.30). One large, localized channel shift of 3.9 m/yr occurred in 2021 around RM 12,200. The channel eroded the bank on river left in 2018 to then deposit a point bar on river right. This caused the wetted channel to shift towards river left.

The 2011 flood left 37 bare surfaces. Relatively the same number of surfaces became vegetated, partly vegetated, and bare in 2018 while four surfaces were incorporated into the wetted channel (Figure 2.31). Most of the bare surfaces in this reach were 0.3 m – 0.6 m above the modern channel (Figure 2.31), however there was no pattern in elevation for which surfaces became vegetated, partly vegetated, wetted channel, or remained unvegetated. There was also no apparent difference in the location of the bare surfaces of which all were located inside or outside channel bends or directly next to these bends.

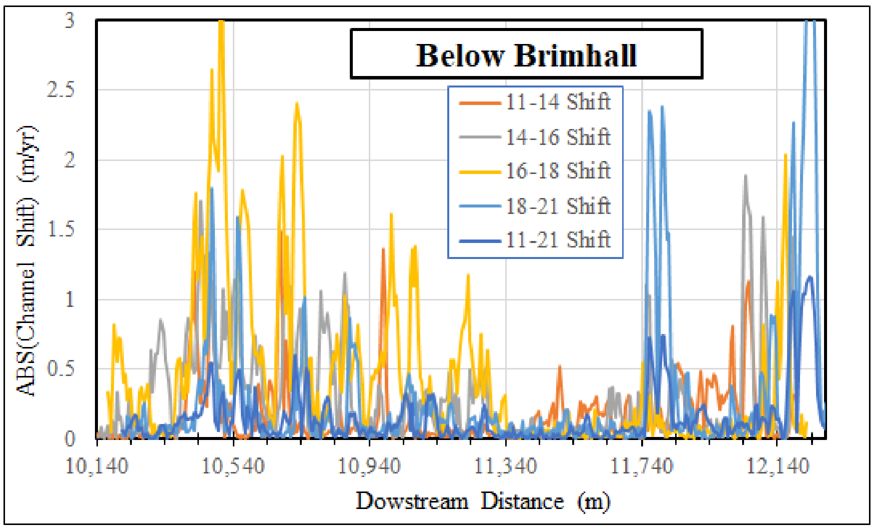

Figure 2.30. Downstream distance (m) vs. the absolute value of the amount of channel centerline shift (m/yr) from 2011-2021 for the Below Brimhall reach.

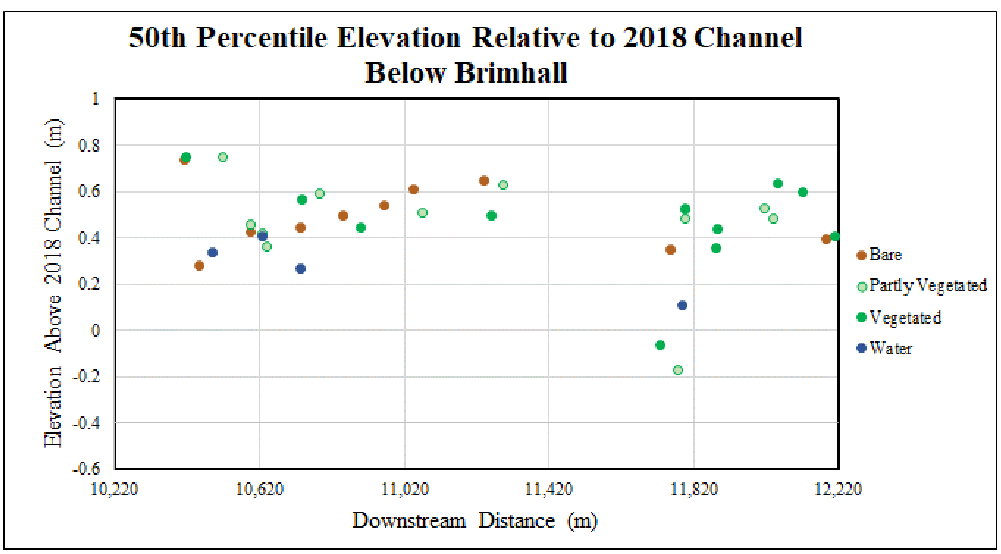

Figure 2.31. 50th percentile elevation relative to the 2018 channel of the unvegetated surfaces from the 2011 flood and their vegetation classification in 2018 for the Below Brimhall reach.

3.8 Levee (Reach 8)

The LDFK in the 1.4 km Levee reach has a 0.6% slope and is unconfined but constrained by the Diamond Fork Road on the right and terraces on the left (Figure 2.32). The riverbed is coarse gravel with some mobile sediment in the present regime.

In total, there was around 3.0 m of channel narrowing from 2011 to 2021, which is about a third of the channel width (Figure 2.33). There were two apparent steps in this channel narrowing from 2011-2016 and from 2018-2021 (Figure 2.33). It appeared that narrowing slowed down from 2016-2018. Bar deposition with most instances being point bar deposition, narrowed the channel between 2011 and 2016 throughout its length.

Around RM 12,600, a significant channel shift of 5.2 m/yr occurred (Figure 2.34) due to bar cutting and bar deposition between 2016 and 2018. The channel cut through a bar on river right in 2016 and then a different bar was deposited on river left in 2018 causing the channel to switch sides. The channel shifted again in 2021 in this section of the reach (Figure 2.34) due to continued bar deposition on river left and erosion on river right.

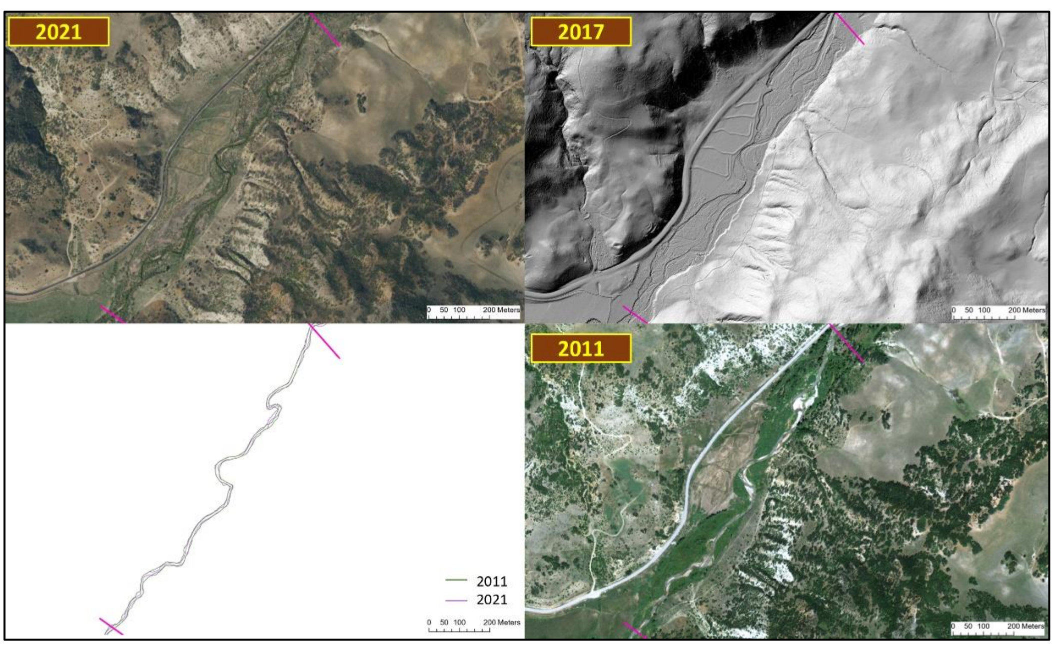

Figure 2.32. Levee reach in 2011, 2017, and 2021 and the bank lines of the 2011 and 2021 active channels.

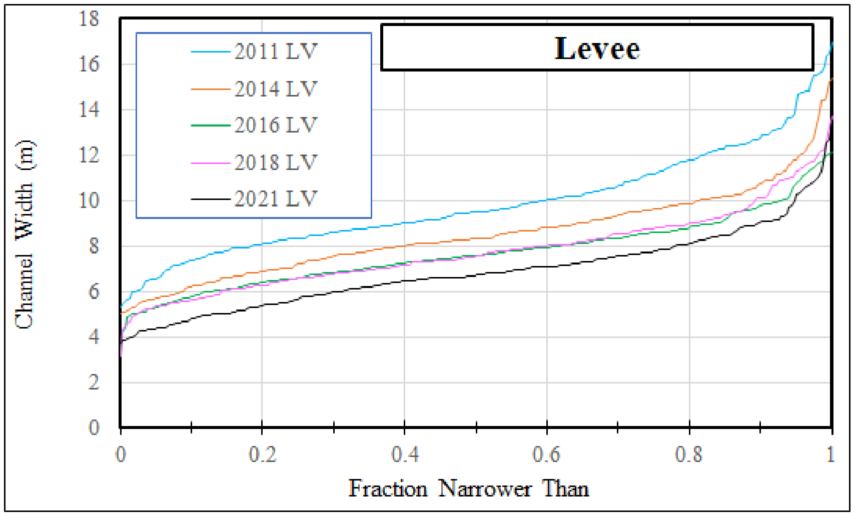

Figure 2.33. Cumulative distribution of channel width (m), 2011-2021, for the Levee reach.

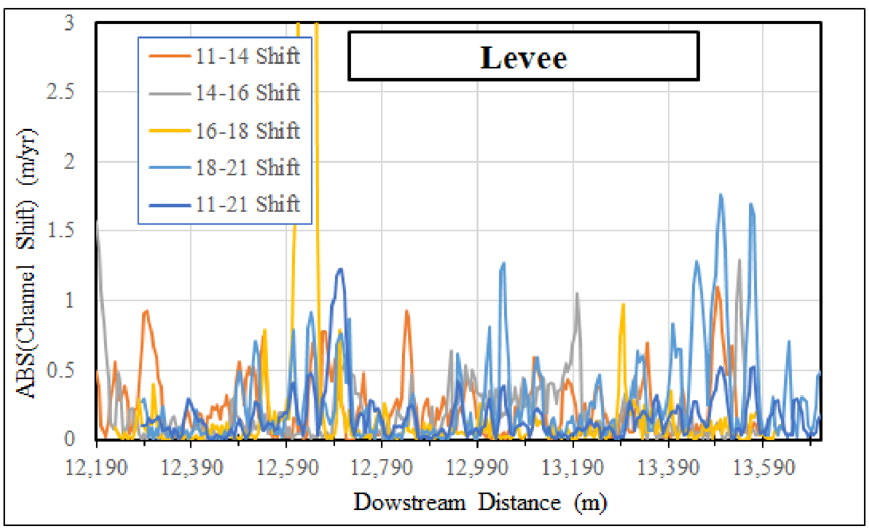

Figure 2.34. Downstream distance (m) vs. the absolute value of the amount of channel centerline shift (m/yr) from 2011-2021 for the Levee reach.

Bends became slightly more elongated in this reach from 2018-2021 due to point bar deposition and outer bank erosion. By 2021 these point bars were vegetated. There was no channel narrowing or shifting in the straighter parts of this reach.

The 2011 flood left 44 bare surfaces. Seven surfaces were integrated into the wetted channel. Five were vegetated, 11 were partly vegetated, and the remaining 21 surfaces remained

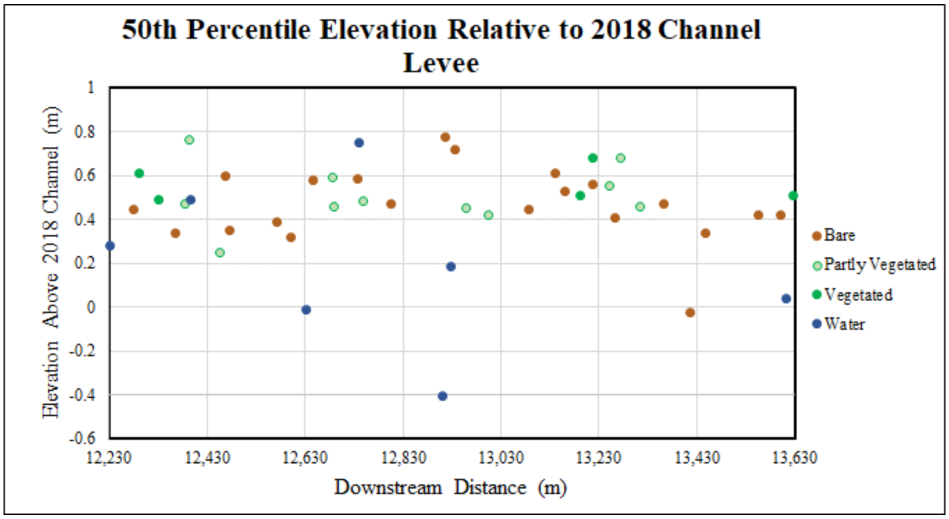

Figure 2.35. 50th percentile elevation relative to the 2018 channel of the unvegetated surfaces from the 2011 flood and their vegetation classification in 2018 for the Levee reach.

unvegetated (Figure 2.35). The majority of the bare surfaces were between 0.2 m and 0.7 m above the modern channel (Figure 2.35), however there is no pattern in elevation for which surfaces became vegetated, partly vegetated, wetted channel, or remained unvegetated. It is hard to tell why this is so, but in this reach, the vegetated surfaces were located in straighter sections of the river, while the surfaces that were partly vegetated, unvegetated, and integrated into the wetted channel were located in inside or outside channel bends.

3.9 Motherlode (Reach 9)

The LDFK channel in the 1.4 km Motherlode reach has a 0.6% slope and is unconfined. The riverbed is medium to coarse gravel with some mobile sediment in the present regime.

Motherlode is located in a largely unconfined valley setting (Figure 2.36), therefore allowing for more lateral channel change. A bit more channel narrowing occurred in the wider sections of the Motherlode reach compared to narrower sections of this reach (Figure 2.37). In total, the channel narrowed almost 3 m, approaching perhaps 30% of its width from 2011-2021 with the wider sections of the channel narrowing slightly more (Figure 2.37). There were two apparent steps in this channel narrowing from 2011-2016 and from 2018-2021 (Figure 2.37). It

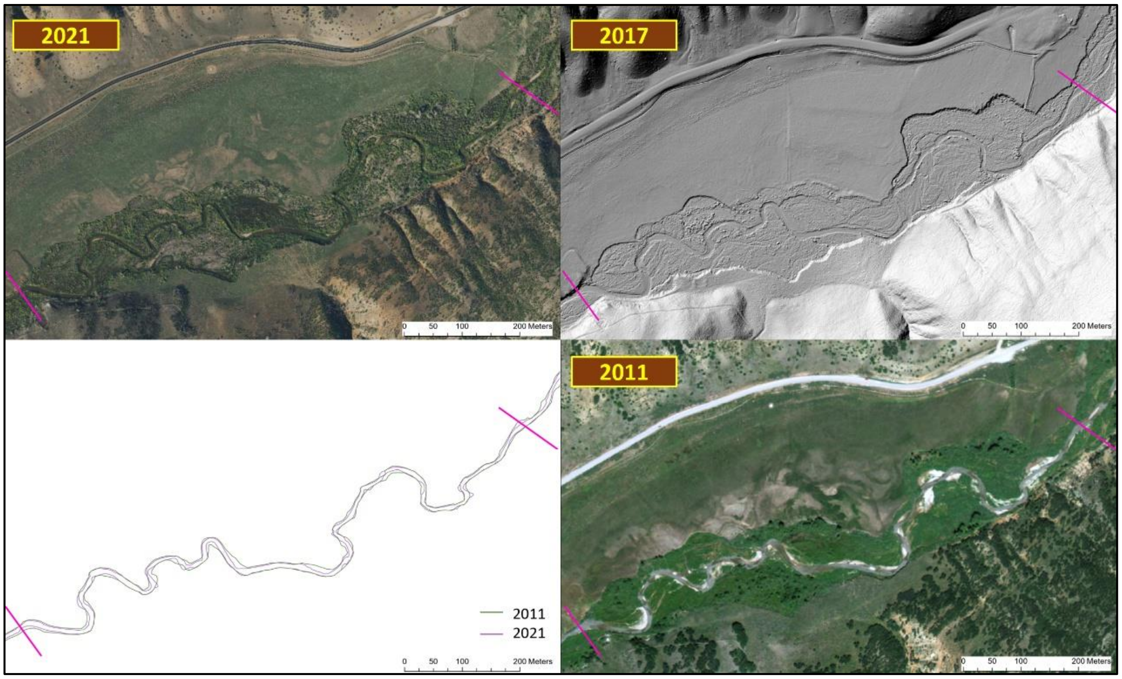

Figure 2.36. Motherlode reach in 2011, 2017, and 2021 and the bank lines of the 2011 and 2021 active channels.

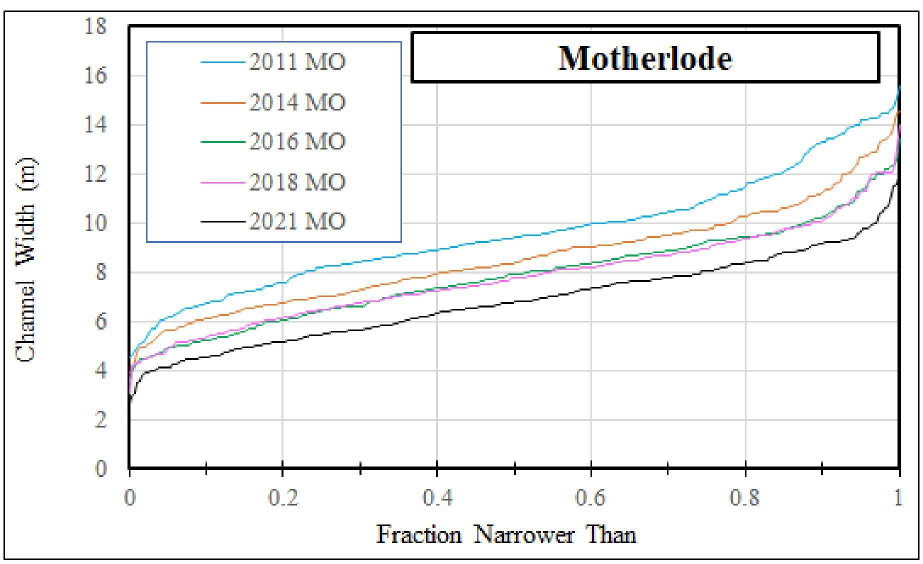

Figure 2.37. Cumulative distribution of channel width (m), 2011-2021, for the Motherlode reach.

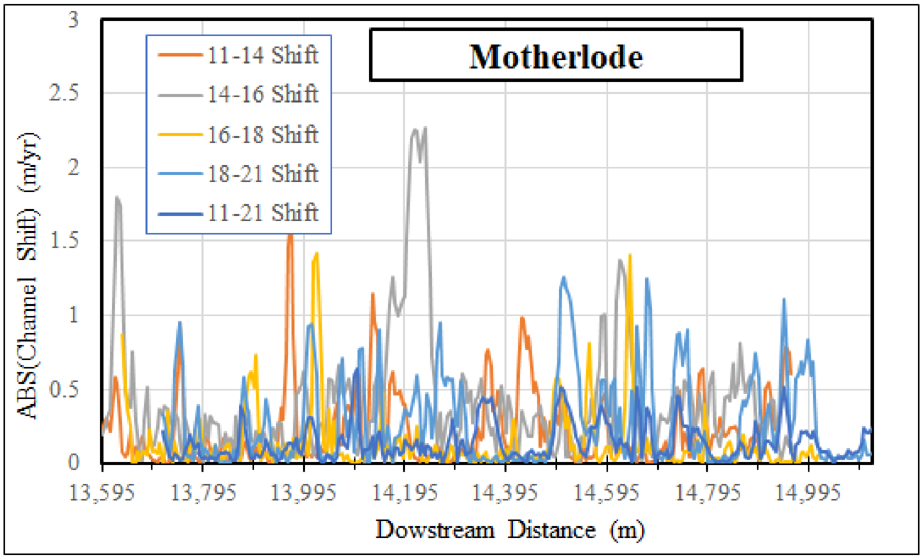

Figure 2.38. Downstream distance (m) vs. the absolute value of the amount of channel centerline shift (m/yr) from 2011-2021 for the Motherlode reach.

appeared that narrowing slowed down from 2016-2018. Point bar deposition, with some instances of just bar deposition narrowed the channel between 2011 and 2016 throughout its length.

Channel shifting from 2011-2014 (Figure 2.38) was primarily due to point bar deposition and outer bank erosion allowing bends to become more elongated. The two largest channel shifts from 2014-2016 (Figure 2.38) were due to bar deposition, while more minor channel shifting was due to bank erosion. Six bends got slightly more elongated between 2011 and 2016 due to point bar deposition and outer bank erosion.

Point bar deposition and outer bank erosion caused the channel to narrow in places from 2016-2021. Many of these bars appeared vegetated by 2021. These point bars caused the channel to narrow consistently across five major bends in the reach. Some erosion on river right also appeared to be slightly shifting these bends as well. Channel narrowing occurred primarily in actively shifting bends. Most of the bends in Motherlode were active, therefore the largest narrowing and shifting was observed in the Motherlode reach. This area contained the most bends in the river and is located in an unconfined valley setting, allowing for more lateral movement compared to the other reaches.

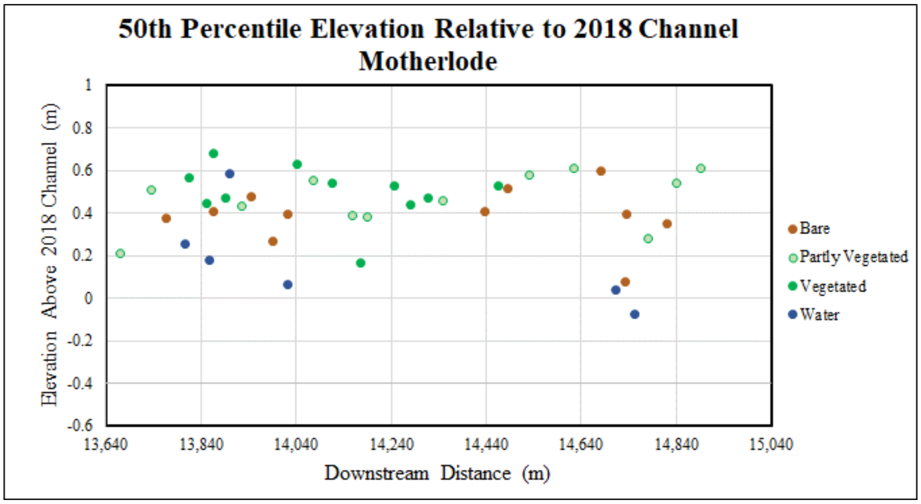

Figure 2.39. 50th percentile elevation relative to the 2018 channel of the unvegetated surfaces from the 2011 flood and their vegetation classification in 2018 for the Motherlode reach.

The 2011 flood left 40 bare surfaces. Relatively the same number of surfaces became vegetated, partly vegetated, and bare in 2018, with six surfaces integrated into the wetted channel (Figure 2.39). The majority of the surfaces were located 0.2 m – 0.6 m above the modern channel (Figure 2.39). Typically, the surfaces that became part of the wetted channel were the lowest in elevation. There is no strong pattern in elevation for which surfaces became vegetated, partly vegetated, wetted channel, or remained unvegetated. All bare surfaces occurred on channel bends, both the inner and outer banks. There was no distinction in vegetation status between surfaces location on the inside or outside of bend.

3.10 Upper Oxbow (Reach 10)

The LDFK in the 0.8 km upper Oxbow reach has a 0.7% slope and is unconfined (Figure 2.40). The riverbed is medium to coarse gravel with some mobile sediment in the present regime.

The channel narrowed around 3.0 m from 2011-2021 (Figure 2.41). About 1.0 m of channel narrowing occurred from 2011-2014 due to some bar deposition and channel shifting. The channel then narrowed another 1.5 m from 2014-2016 (Figure 2.41) again due to bar deposition and channel shifting. A small island around RM 15,700 in the 2014 channel became a

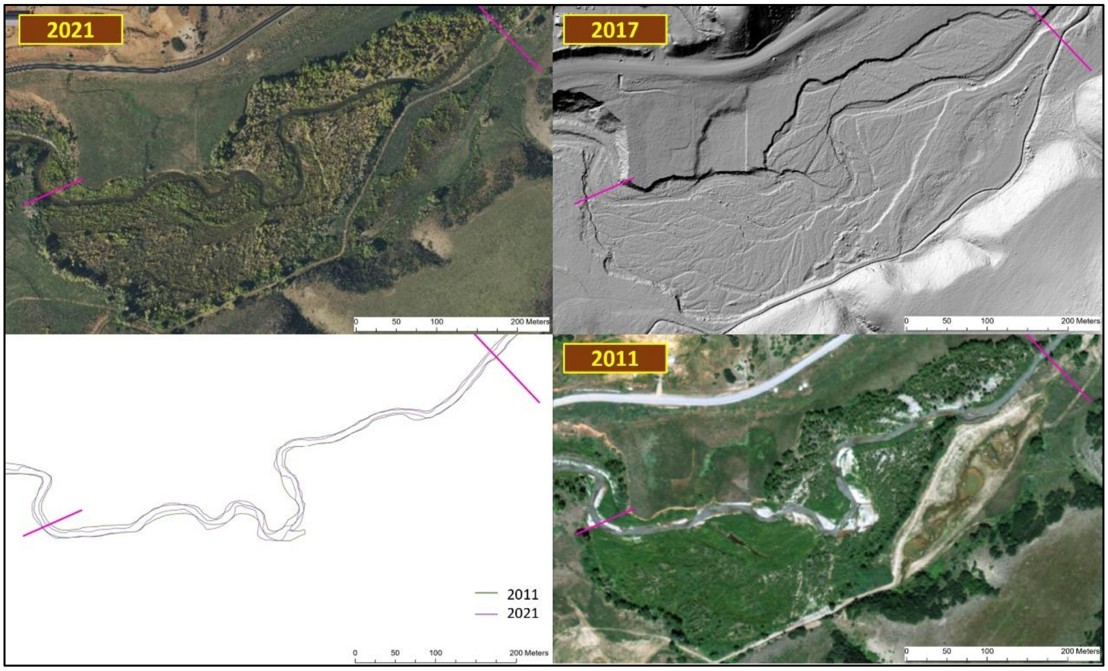

Figure 2.40. Upper Oxbow reach in 2011, 2017, and 2021 and the bank lines of the 2011 and 2021 active channels.

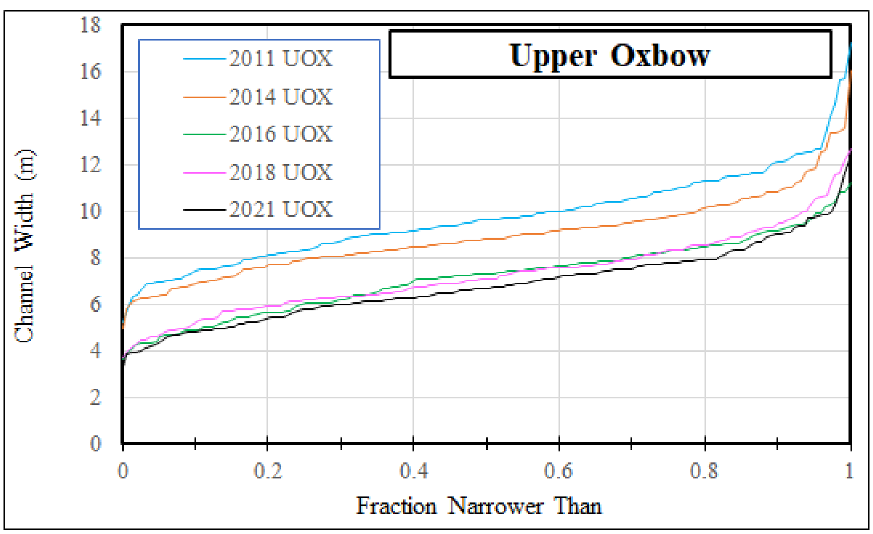

Figure 2.41. Cumulative distribution of channel width (m), 2011-2021, for the upper Oxbow reach.

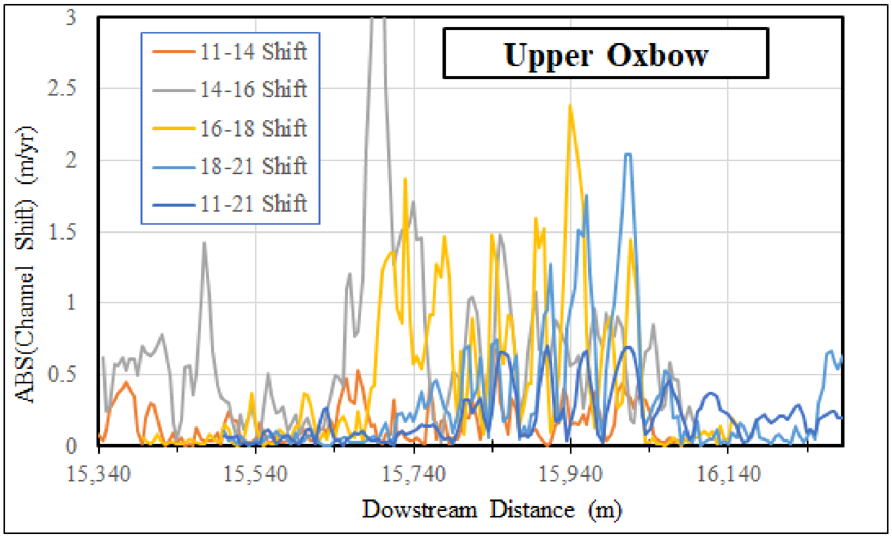

Figure 2.42. Downstream distance (m) vs. the absolute value of the amount of channel centerline shift (m/yr) from 2011-2021 for the upper Oxbow reach.

bar by 2016, thus causing the channel to narrow in that section. Channel narrowing became steadier from 2016-2018. Bar deposition and outer bank erosion occurred again from 2018-2021 which caused another period of channel narrowing (Figure 2.41).

Four bends (RM 15,700, RM 15,800, RM 15,880, RM 15,980) in this reach became narrower and more elongated from 2011-2018 due to point bar deposition and outer bank erosion. A large channel shift from 2014-2016 of 3.90 m/yr (Figure 2.42) was caused by point bar deposition and outer bank erosion. Only the more upstream three of the four bends mentioned continued to elongate from 2018-2021 due to point bar deposition and outer bank erosion. These point bars were then observed to be vegetated in 2021. Even with this channel change, the width of the channel did not change much as erosion and deposition compensated each other.

The 2011 flood left 12 bare surfaces. No surfaces were integrated into the wetted channel. Six were vegetated, two were partly vegetated, and the remaining four surfaces remained unvegetated. The majority of the surfaces were around 0.6 m above the modern channel (Figure 2.43), however there is no pattern in elevation for which surfaces became vegetated, partly vegetated, or remained unvegetated. The higher surface of 1.4 m elevation (Figure 2.43) appears

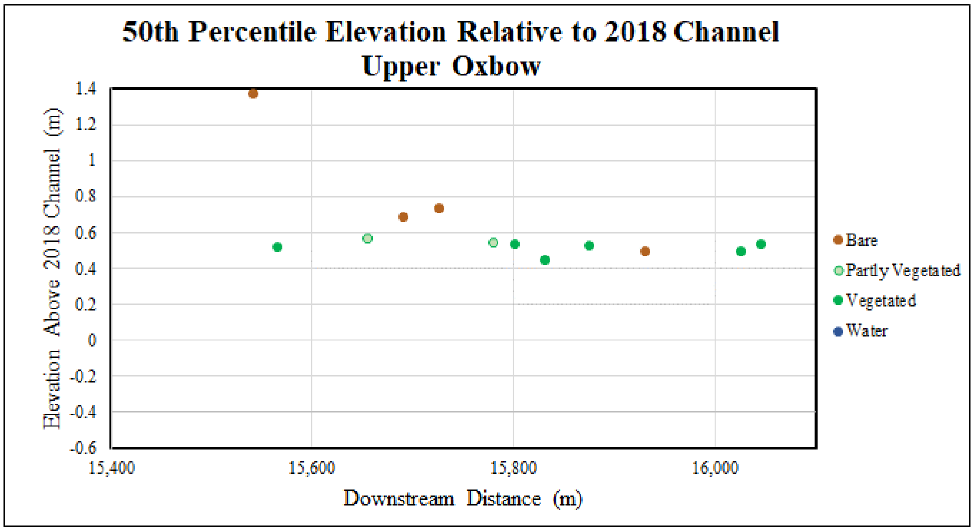

Figure 2.43. 50th percentile elevation relative to the 2018 channel of the unvegetated surfaces from the 2011 flood and their vegetation classification in 2018 for the upper Oxbow reach.

to be located on the edge of a terrace, making it higher in elevation compared to the other surfaces. Most of the 2011 surfaces were located on channel bends.

3.11 Lower Oxbow (Reach 11)

The LDFK in the 0.6 km lower Oxbow reach has a 0.6% slope and is unconfined. The riverbed is medium to coarse gravel with some mobile sediment in the present regime.

The majority of lower Oxbow is one large bend in both the valley and river (Figure 2.44). The wider and narrower sections of the reach narrowed at similar rates with a total of 2.5 m of channel narrowing from 2011-2021 (Figure 2.45). Channel narrowing occurred in two steps between 2011 and 2016 and again from 2018-2021. Channel shifting from 2011-2016 caused narrowing, however, some of the narrowing from 2011-2016 could be due to differences in discharge when the 2011 and 2016 aerial photos were captured. Point bar deposition and outer bank erosion caused narrowing from 2018-2021. Narrowing slowed down from 2016-2018 (Figure 2.45). The most channel narrowing of 1.3 m occurred from 2011-2014 due to channel shifting, although some of this narrowing could be due to shadows in the aerial photos.

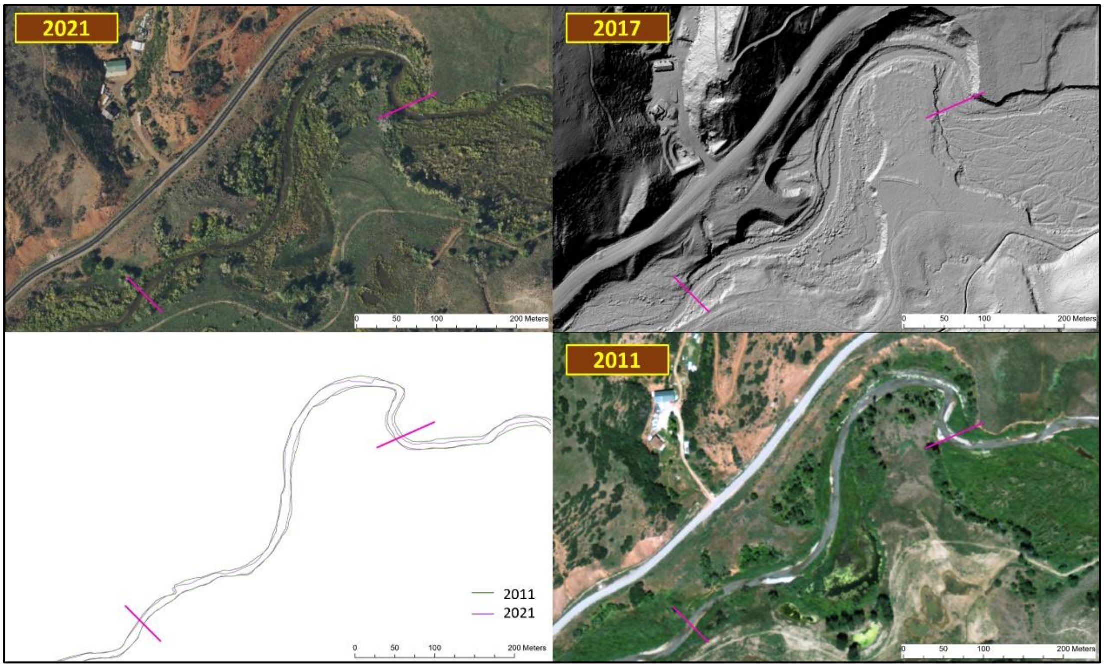

Figure 2.44. Lower Oxbow reach in 2011, 2017, and 2021 and the bank lines of the 2011 and 2021 active channels.

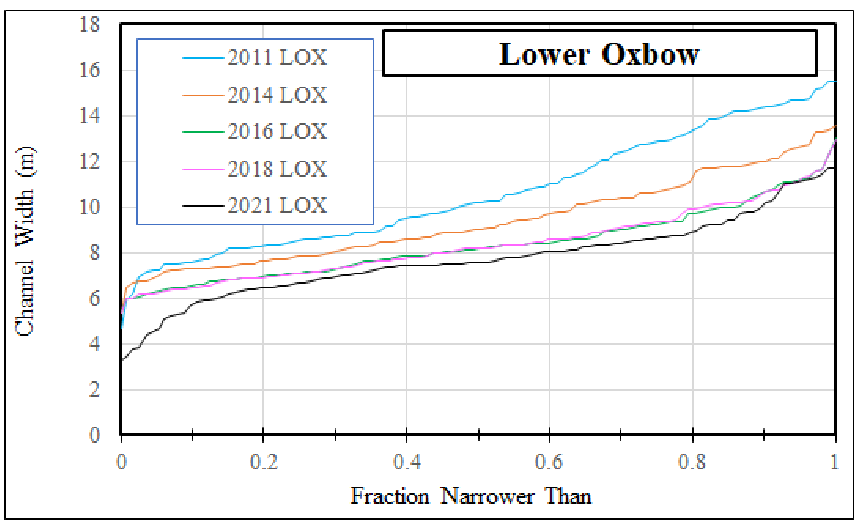

Figure 2.45. Cumulative distribution of channel width (m), 2011-2021, for the lower Oxbow reach.

At RM 16,300, point bar deposition and outer bank erosion from 2016-2021 caused a relatively smaller bend to narrow and elongate. This bar was vegetated by 2021. A large bend in this reach (around 16,400 m downstream) narrowed and shifted (Figure 2.46) due to bar deposition between 2018 and 2021 (Figure 2.47) causing this section of the reach to be almost 5 m narrower in 2021 than in 2018. This bar was vegetated by 2021.

The 2011 flood left 12 bare surfaces. One lower surface was integrated into the wetted channel. Eight were vegetated, one was partly vegetated, and the remaining two surfaces remained unvegetated. The majority of the surfaces were around 0.3 m – 0.6 m above the modern channel (Figure 2.48), however there is no strong pattern in elevation for which surfaces became vegetated, partly vegetated, or remained unvegetated. The 2011 bare surfaces were all located in channel bends, both on the inner and outer banks. There was no difference in geomorphic position for the different vegetation categories.

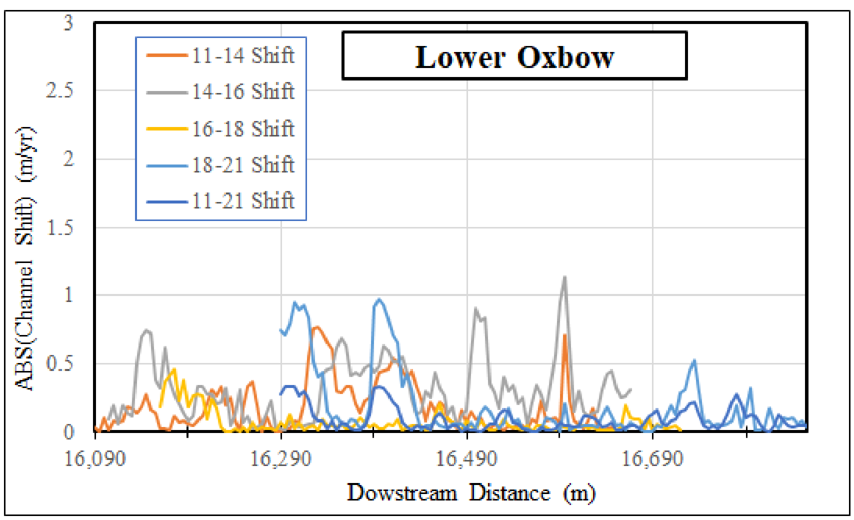

Figure 2.46. Downstream distance (m) vs. the absolute value of the amount of channel centerline shift (m/yr) from 2011-2021 for the lower Oxbow reach.

Figure 2.47. Bar deposition between 2018 and 2021 in the lower Oxbow reach.

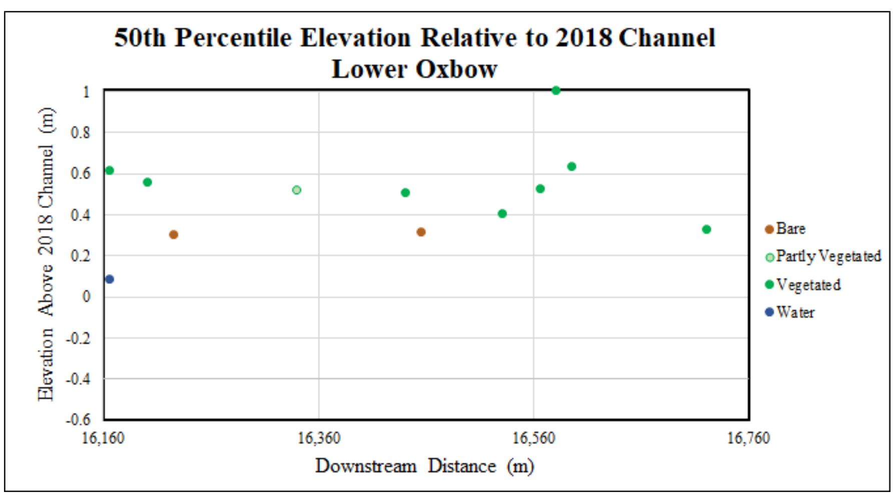

Figure 2.48. 50th percentile elevation relative to the 2018 channel of the unvegetated surfaces from the 2011 flood and their vegetation classification in 2018 for the lower Oxbow reach.

3.12 Upper and Lower Childs (Reaches 12 and 13)

The LDFK in the 1.5 km Childs reach is the furthest downstream reach. The distance from the bottom of the reach to the confluence with Spanish Fork River is roughly 0.6 km. This reach has a 0.5% slope and is unconfined (Figure 2.49). The riverbed is medium to coarse gravel with some mobile sediment in the present regime.

In total, the channel narrowed about 2.0 m from 2011-2021 (Figure 2.50). Less narrowing occurred in the narrower sections of the upper and lower Childs reaches compared to the wider sections of the reach. (Figure 2.50). Point bar deposition and outer bank erosion caused the most amount of channel shifting from 2018-2021 (Figure 2.51). Some channel shifting from 2014-2016 may be due to seasonal growth of grasses.

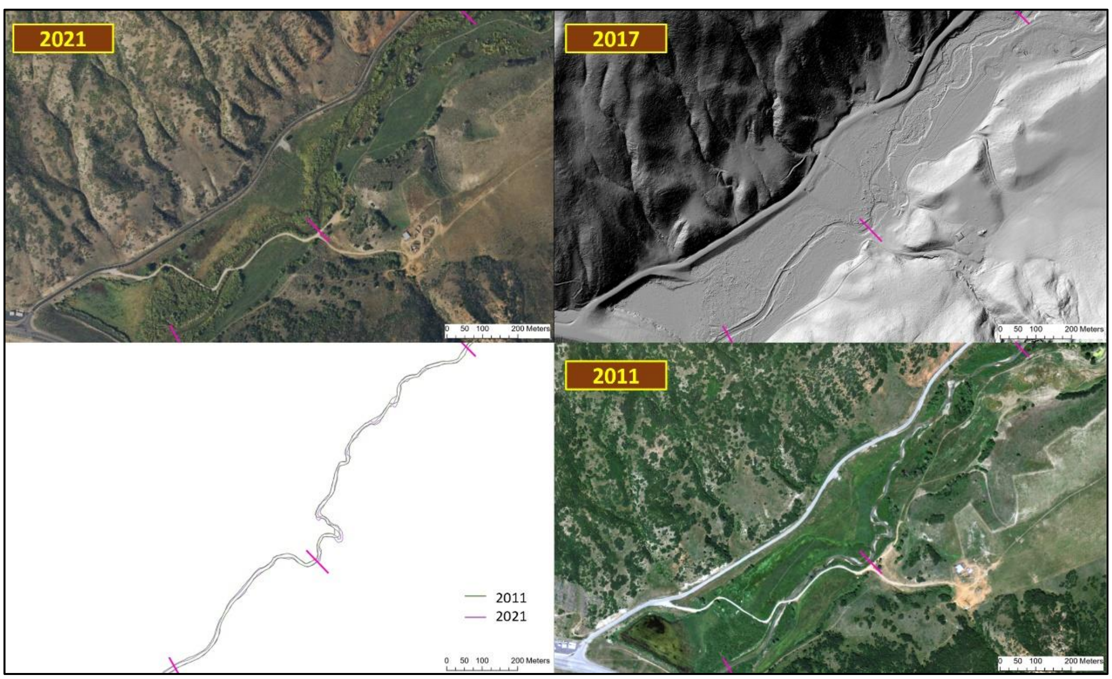

Figure 2.49. Upper and lower Childs reach in 2011, 2017, and 2021 and the bank lines of the 2011 and 2021 active channels.

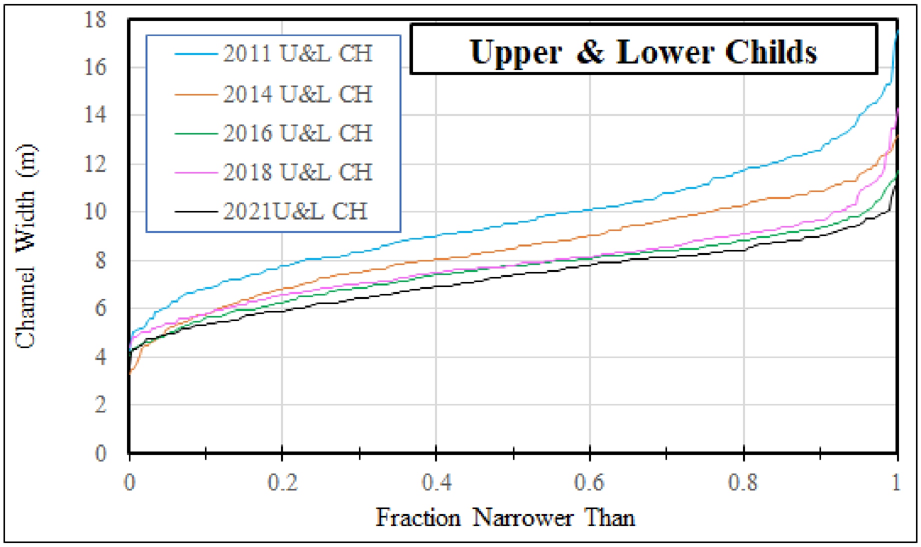

Figure 2.50. Cumulative distribution of channel width (m), 2011-2021, for the upper and lower Childs reach.

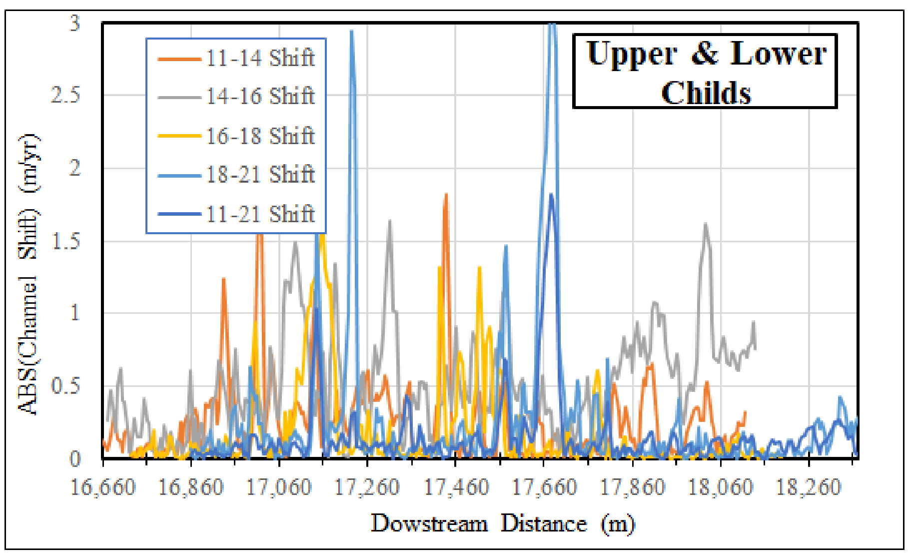

Figure 2.51. Downstream distance (m) vs. the absolute value of the amount of centerline channel shift (m/yr) from 2011-2021 for the upper and lower Childs reach.

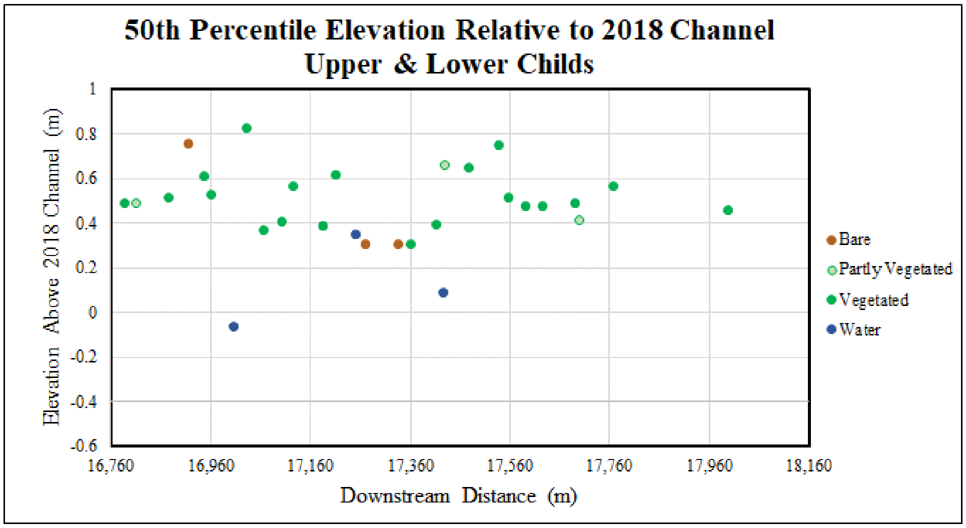

Figure 2.52. 50th percentile elevation relative to the 2018 channel of the unvegetated surfaces from the 2011 flood and their vegetation classification in 2018 for the upper and lower Childs reach.

In the upper Childs reach, there was consistent channel narrowing due bar development from 2011-2014. Point bar growth from 2011-2016 caused these bends to become more elongated. Channel shifting and narrowing occurred between 2016 and 2021 due to bar development in 2018 with these bars observed to be vegetated by 2021.

Two major localized channel shifts occurred from 2018-2021 in the upper Childs reach around RM 17,225 and RM 17,675 (Figure 2.51). The first was caused by the river cutting through a bar and establishing a point bar on the opposite bank. This new bar was vegetated by 2021. The second, producing a 3.4 m/yr shift (Figure 2.51), was caused by bend growth via point bar deposition and outer bank erosion. The point bar was vegetated in 2021. Overall, four bends narrowed and elongated from 2018-2021 due to point bar deposition and outer bank erosion and all bars were vegetated by 2021.

One short reach—around RM 17,960—became narrower from 2016-2021, due to bar development in 2018 with this bar vegetated by 2021.

The 2011 flood left 29 bare surfaces. Three surfaces were integrated into the wetted channel. The majority of the surfaces were vegetated, three were partly vegetated, and three surfaces remained unvegetated (Figure 2.52). Most of the surfaces were 0.3 m – 0.6 m above the modern channel (Figure 2.52), however there is no strong pattern in elevation for which surfaces were integrated into the wetted channel, became vegetated, partly vegetated, or remained unvegetated. The lower elevation surfaces were integrated into the wetted channel, however only three wetted surfaces were identified. The majority of the surfaces in this reach were identified as vegetated surfaces in 2018. All surfaces were located inside or outside channel bends causing no apparent difference in location of the bare surfaces.

4. Discussion

The Diamond Fork River provides an opportunity to understand how a channel recovered after the elimination of flow augmentation and how the river has continued to change in the last decade with elevated artificial base flows. Seven years after the augmented flows were removed from the Diamond Fork system in 2004, a modestly large flood of 735 ft^3/s occurred in 2011 and disturbed the post-diversion channel. This study focuses on channel change in the 11 years following the flood, with the goal of identifying the mechanisms of channel change and the locations where complex habitat is being maintained or created. This provides a basis for evaluating alternatives for restoration actions to improve habitat.

A previous study suggested that vegetation establishment on the LDFK may be limited by elevated baseflows that cover the channel bottom throughout the summer growing season, and thereby limit channel narrowing (Jones et al., 2023). With more detailed mapping by extending the period of observation from 2016 to 2021, we were able to identify that the channel has narrowed since 2016. This detailed mapping allowed us to identify the channel change mechanisms from 2011-2021 and how and where channel change is occurring. Our goal is to inform river restoration alternatives regarding how the channel habitat might continue to change.

4.1 Mechanisms of Channel Change

Four main mechanisms of channel change were identified. The first was bend growth and shift via point bar deposition and outer bank erosion. Actively shifting channel bends tended to become narrower and more elongated (Figure 2.53). This was the dominant channel change mechanism during this 11-year period on the LDFK. The majority of the channel change during this study period occurred in channel bends.

The second mechanism was bar deposition not associated with channel bends. This made the channel narrower as sediment deposited in the channel creating a bar which decreased the width of the channel (Figure 2.54). At times, these bars were observed to be vegetated.

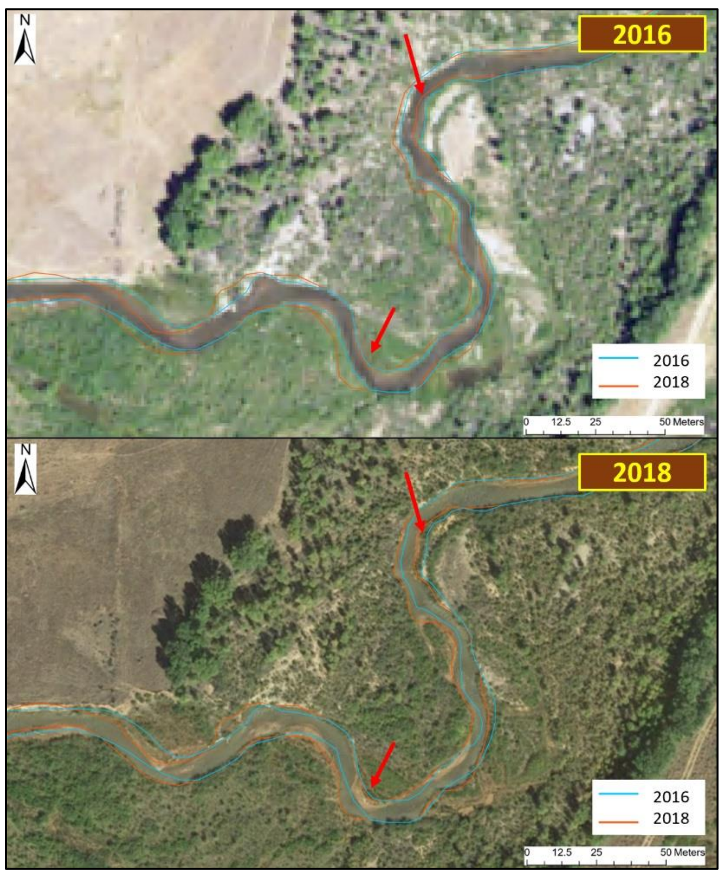

Figure 2.53. Examples of bend growth and shift via point bar deposition and outer bank erosion from 2016-2018 in the lower Oxbow reach.

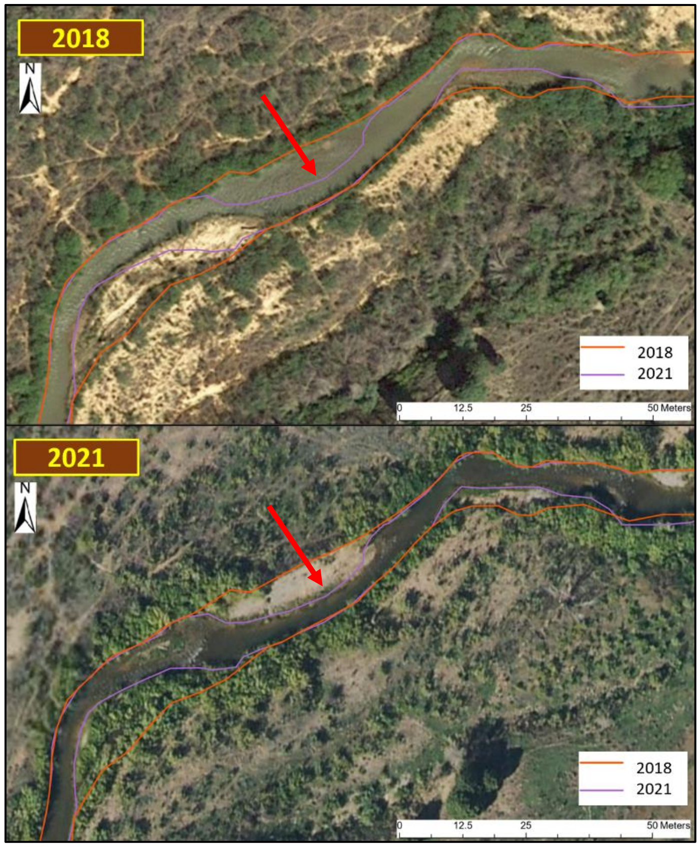

Figure 2.54. Example of bar deposition from 2018-2021 in the Levee reach.

The third mechanism was bar cutting with associated deposition of a new bar downstream. The wetted channel cut through a bar on one side of the river to then deposit another bar on the opposite side of the river. This caused the river to shift from one side of the river to the other (Figure 2.55). This was the least frequent mechanism of channel change on the lower Diamond Fork River from 2011-2021 as it only occurred twice—once from 2016-2018 in the Levee reach and once from 2018-2021 in the Childs reach. The fourth channel change mechanism is driven by the occurrence of channel spanning wood jams (Figure 2.56). Three wood jams were observed on the LDFK—one in the Dry Canyon reach and two in the Monks Hollow reach—all in the upstream section of the river. Flooding above these wood jams forced the flow to one side, causing large channel shifts in two locations in 2021 and one location in 2018. Both bar cutting wood jams produced a large, localized channel change, but were the least frequent mechanisms

Figure 2.55. Example of bar cutting and bar deposition from 2016-2018 in the Levee reach.

Figure 2.56. Example of a wood jam from 2016-2018 in the Monks Hollow reach.

observed. Even though these wood jams shifted the river flow and aquatic habitat (Vaz et al., 2013), more channel change occurred without the influence of wood.

Although instream wood can directly influence the complexity of channel habitat, there is little wood found in the present channel. Most of the channel change observed occurred in channel bends, particularly in the lower half of the reach where the channel is unconfined and more fine sediment is available to support growth of riparian vegetation.

4.2 Patterns in 21st century channel change

In the last decade, channel narrowing occurred primarily in the downstream section of the river from Below Brimhall Bridge downstream to Childs. This downstream section is located in a largely unconfined valley setting whereas the upstream section is in a largely confined to partially confined valley setting. This confinement limited the width of the channel and any meander belt. The LDFK is now approaching a relatively constant width of 7 m to 9 m. The earlier constraints on exceptional widening during the flow diversion period also limits the proportional amount of widening possible in the last decade.

Channel narrowing from 2011-2021 in the lower half of LDFK, from Below Brimhall Bridge to Childs, was about 2 m to 3 m, or about 20% to 30% of the 2011 channel width (Figure 2.57). Over this decade, the mean centerline shift of 1 m or less occurred above Brimhall Bridge, whereas centerline shift of 1.5 m to 2 m occurred downstream of Brimhall Bridge (Figure 2.58). Four spikes in the lateral shift running average are evident in Figure 2.58. The first spike around RM 3,000 was due to the large wood jam causing a localized avulsion between 2016 and 2018 in the Monks Hollow reach (Figure 2.56.). The second spike around RM 12,500 was due to bar cutting that occurred in the Levee reach from 2016-2018 (Figure 2.55), in which the channel cut through a bar on river right and deposited a new bar on river left. The third spike, around RM 16,300 was due to bar deposition from 2018-2021 which narrowed the channel in the lower

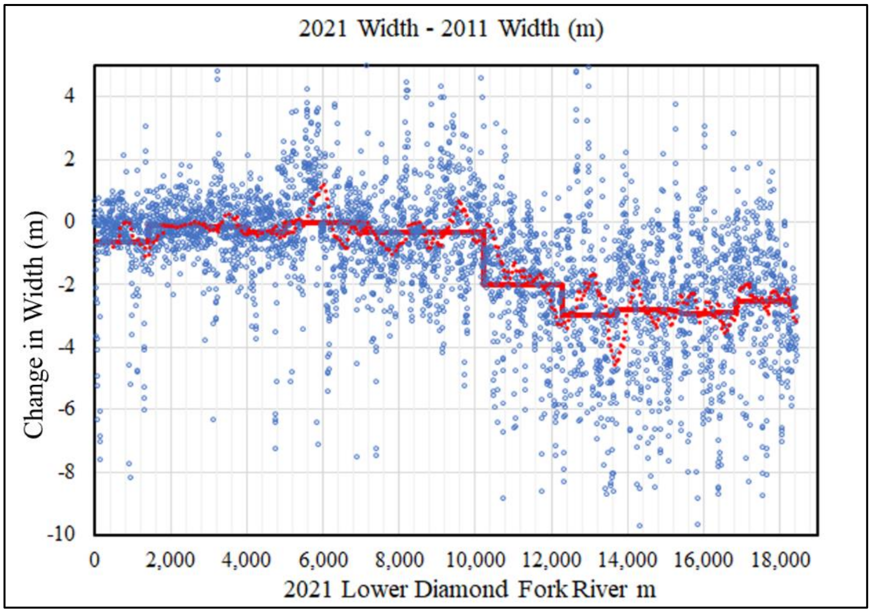

Figure 2.57. Differences in channel width (m) from 2011-2021 over the length of the lower Diamond Fork River. Red dots are running average of 100 pts (500 m). Red lines are mean for each reach.

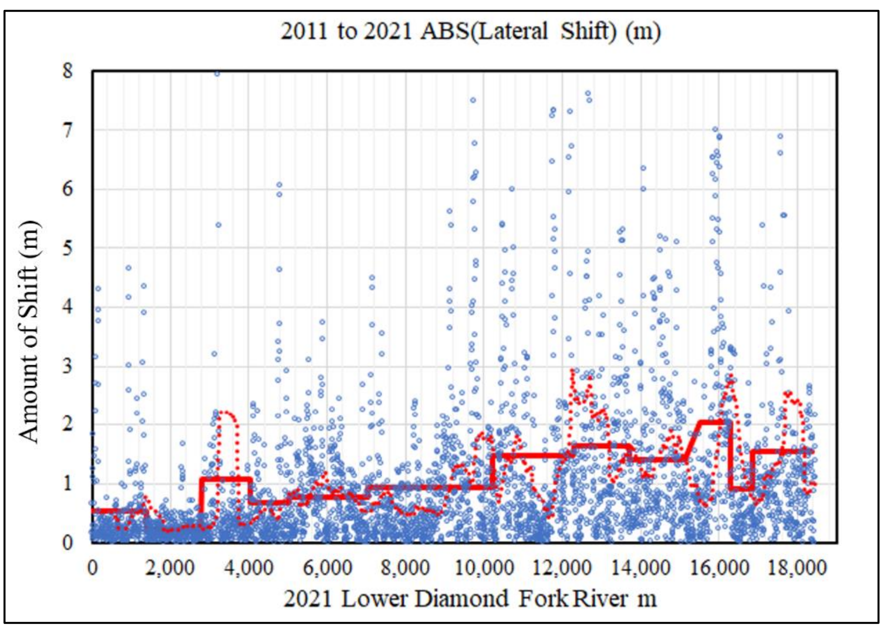

Figure 2.58. Differences in lateral channel centerline shift (m) from 2011-2021 over the length of the lower Diamond Fork River. Red dots are running average of 100 pts (500 m). Red lines are mean for each reach.

Oxbow reach. The fourth spike in lateral shift around RM 17,500 was due to extensive point bar deposition and outer bank erosion between 2016 and 2021 in the Childs reach.

Channel narrowing appears to have occurred at different rates over the 2011-2021 study period. The largest amount of channel change happened from 2011-2016. After 2011-2016, the pace of narrowing appeared to slow down from 2016-2018 (Figure 2.59). Channel narrowing increased again from 2018-2021, however only from Below Brimhall Bridge downstream to Childs (Figure 2.59). This suggests that there were two distinct periods of channel narrowing that occurred during the 11-year period. It is unclear why the narrowing slowed down between 2016 and 2018. The discharge did decrease by half from the 2014 aerial images to the 2016 aerial images, however the discharge only increased by 10 ft^3/s and therefore did not drastically change between 2016 and 2018. As a result, the pace of narrowing from Below Brimhall Bridge to Childs may be more uniform than shown (Figure 2.59) Based on the aerial imagery, it appeared that there was more vegetation near the banks of the 2021 channel compared to the 2018 channel. One possibility for this could be from a lower base flow starting in 2017.

Overall, the greatest amount of channel shifting occurred between 2016 and 2018 from Monks Hollow downstream to Below Brimhall Bridge and between 2014 and 2016 from Motherlode downstream to Childs (Figure 2.60). Very little channel shifting occurred in the Dry Canyon and Below Dry Canyon reaches. There was a significant increase in the amount of channel shifting between 2011 and 2014 and between 2014 and 2016 (Figure 2.60). Some of this could be due to methodological error in channel mapping, however, numerous point bar deposits were observed during this time, which influenced the channel shifting.

Based on the 2021 aerial imagery, more vegetation was observed on the banks of the 2021 channel compared to previous years, specifically the 2018 channel. Many of the point bars deposited in 2018 were vegetated by 2021. Thus, the vegetation completes a process in which sediment deposits narrow the channel and the vegetation holds the sediment in place. No formal vegetation density measurements were made; however, vegetation density is visibly greater in

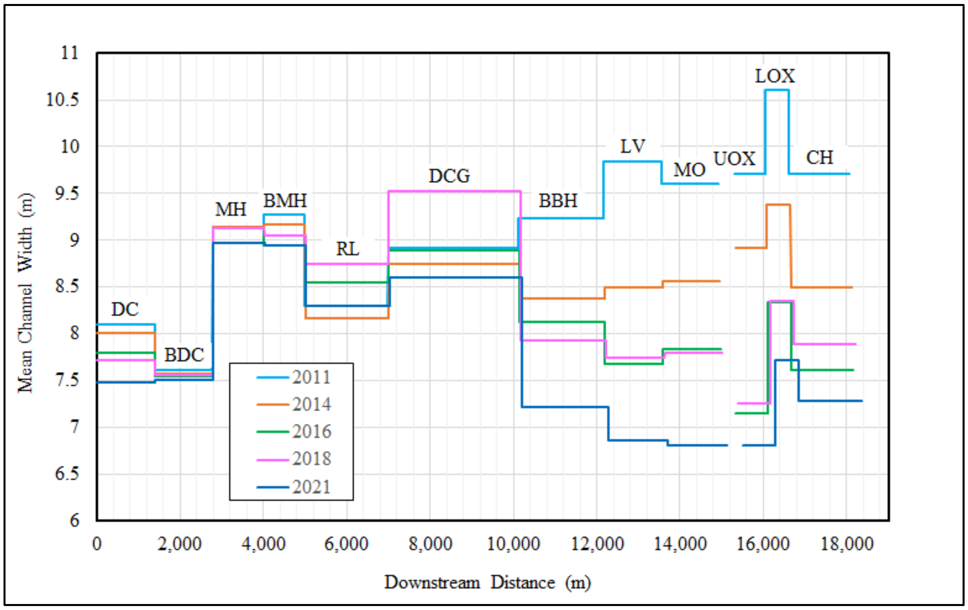

Figure 2.59. Mean channel width (m) over the length of the LDFK going downstream from the confluence with SXW from 2011-2021.

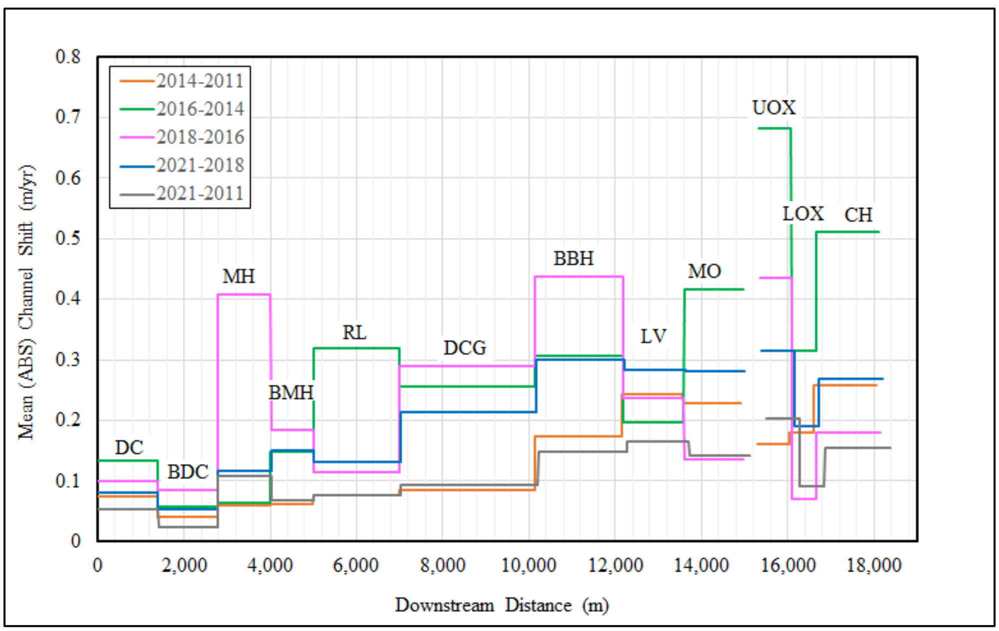

Figure 2.60. Mean channel centerline shift (m) over the length of the LDFK going downstream from the confluence with SXW from 2011-2021.

2021 than 2018 (Figure 2.61, Figure 2.62), specifically from Diamond Campground downstream to Childs. The downstream portion of the LDFK (Diamond Campground to Childs) appeared to contain denser vegetation than the upstream section (Dry Canyon to Red Ledges). This could be due to finer grain sizes in the downstream section compared to the upstream section. This is further discussed in section 4.3.

Figure 2.61. Example of the increase in vegetation density from 2018 to 2021 in the Levee reach. Red arrows display locations to focus on.

Figure 2.62. Example of the increase in vegetation density from 2018 to 2021 in the Motherlode reach. Red arrows display locations to focus on.

It has been proposed that the LDFK is approaching a new equilibrium geometry in which alluvial deposits and vegetation are limiting the geomorphic change of the river, causing it to reach a constant width throughout the channel (Jones et al., 2023). Closer mapping of the wetted channel (rather than the active channel which included the vegetation-free channel margins) and extending the mapping to 2021 reveal a more complex and different pattern. The mean channel width in 2011 was consistent from Monks Hollow downstream at 9 m to 10 m (Figure 2.59). Channel narrowing from 2011-2021 increased from Diamond Campground downstream (Figure 2.57, Figure 2.59), such that the current channel width is 7.5 m in the upstream reaches of Dry Canyon and Below Dry Canyon, 8.5 m to 9 m from Monks Hollow to Diamond Campground, and 7 to 7.5 m in the more downstream reaches. The lowest reaches, from Below Brimhall Bridge to Childs remains the most dynamic, with greater rates of sediment transport (Wilcock et al., 2019) and greater channel shifting.

4.3 2011 Bare Surface Analysis Observations

The 2011 flood removed vegetation along the banks leaving behind bare surfaces adjacent to the 2011 wetted channel. Some of these surfaces became vegetated by 2018, others did not. In general, the number and frequency of the bare surfaces created in 2011 increased in the downstream direction (Figure 2.63). The largest numbers occurred in the Levee, Diamond Campground, Motherlode, and Below Brimhall reaches from RM 11,000 to RM 15,000. Many of the polygons classified as vegetated and partly vegetated in 2018 also appeared closer to the downstream end of the LDFK. These clusters were from RM 13,000 to RM 18,000 (Figure 2.63).

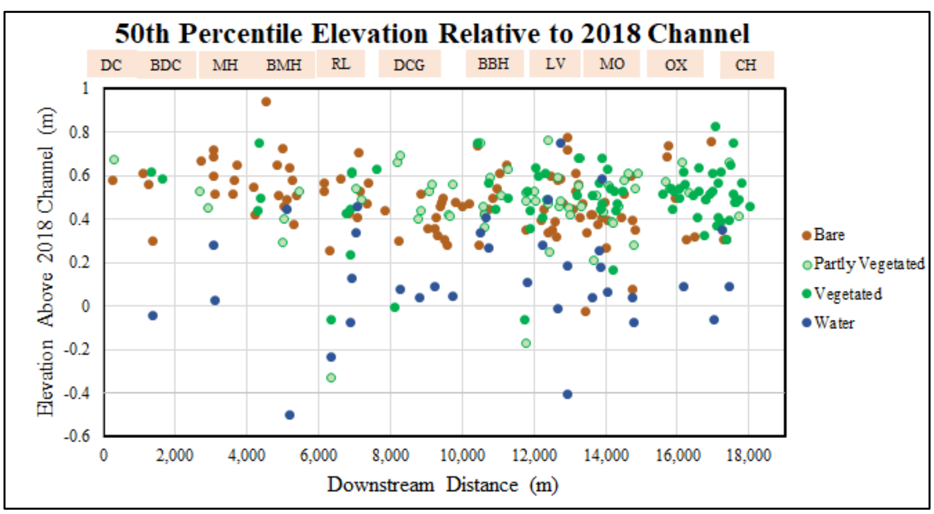

Figure 2.63. 50th percentile relative elevation to the 2018 active channel of all unvegetated surfaces produced by the 2011 flood over the length of the LDFK and their classification based on their vegetation status in 2018. Different colors depict their 2018 classification.

Overall, there was little indication that the vegetated state of the 2011 bare surfaces is connected to height above the modern channel. There is more of a relation with distance downstream and grain size of the surface. Twenty of these surfaces from the Motherlode reach downstream to the Childs reach were visited and we observed that the vegetated surfaces contained more fine-grained material, suggesting that the presence or absence of a fine-grained mantle was more likely to influence establishment of vegetation, regardless of relative elevation of the ground surface. All bare surfaces visited contained gravel with few surface fines. The vegetated surfaces visited all contained a fine-grained mantle that was typically between 10-20 cm thick. Many of the vegetated surfaces had grain sizes of either sand or sandy-silt with a few surfaces containing sandy-clay and clay. It is possible that conditions permitting the deposition and retention of a mantle of sand and finer sediment determine where vegetation can establish and promote channel narrowing.

5. Conclusion

Large diversion flows were removed from the lower Diamond Fork River (LDFK) in 2004. Channel adjustments since that time provide a basis for evaluating future channel conditions. A flood in 2011 disturbed the channel and left many areas next to the channel bare of vegetation. We examine channel change over the period 2011-2021 to evaluate how the channel is currently adjusting and to explore the role of vegetation establishment in channel change.

The channel narrowed from 2011-2021 throughout the LDFK. This narrowing occurred primarily in the downstream section of the river from Below Brimhall Bridge downstream to Childs. The downstream channel is unconfined whereas the upstream section is largely confined to partially confined. This confinement limited the widening of the river during the diversion period and thus the amount of narrowing after the diversion flows ended. The lower reaches remain more dynamic, with more active sediment transport, greater channel shifting particularly in bends, and more robust vegetation colonization of bare surfaces adjacent to the river.

Greater vegetation density was observed on the banks of the 2021 channel compared to previous years, specifically the 2018 channel. Many of the point bars observed in 2018 were vegetated by 2021, suggesting that deposit grain size and amount of water on the channel banks was sufficient for vegetation to grow.

The LDFK channel remained single thread throughout the study period. The majority of channel change occurred on or near channel bends that typically narrowed and elongated from 2011-2021. Most of this change occurred in the largely unconfined valley setting of the river.

Four main channel change mechanisms were identified from 2011-2021: bend growth (point bar deposition and outer bank erosion), bar deposition not associated with channel bends, bar cutting with bar deposition, and the presence of wood jams. Bar cutting with associated bar deposition of a new bar downstream, and the presence of channel spanning wood jams were the two mechanisms that caused the most localized channel change but were the least frequent mechanisms. Point bar deposition and outer bank erosion was the most dominant mechanism from 2011-2021.

The 2011 flood removed vegetation along the banks leaving behind bare surfaces adjacent to the 2011 wetted channel. In general, more bare surfaces were observed on the downstream end of LDFK. Some of these surfaces became vegetated by 2018, others did not. Elevation above the modern river channel does not appear to influence whether vegetation became established. It was observed that the vegetated surfaces contained more fine-grained material, suggesting that the presence or absence of a fine-grained mantle was more likely to influence establishment of vegetation, regardless of relative elevation of the ground surface.

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