FLUVIAL GEOMORPHOLOGY OF THE ENTIAT RIVER, WA, AND IMPLICATIONS FOR STREAM RESTORATION

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Abstract In the Entiat subbasin of the Upper Columbia River Basin, human-induced changes to channel processes are believed to have historically reduced the quality and availability of aquatic habitat (CCCD 2004). The current study was undertaken to provide a long-term context and understanding of geomorphic processes along 26 miles of the Entiat River and to determine the extent that channel processes have been altered during the historical period. Results were utilized to identify areas impacted by human activities and opportunities for protection or restoration of channel and floodplain processes. While some previous work states that human modifications are largely responsible for habitat conditions in the Entiat River, this study demonstrates that channel morphology on a broad scale is influenced by geologic features rather than historically constructed features in the channel. This conclusion is illustrated by the change in stream gradient at geologic features, the presence of alluvial surfaces that are 1,000 years or older adjacent to the stream channel and few detectable impacts to channel pattern from anthropogenic activities. In the upper 10 miles of the study reach, channel morphology can be directly related to the position of alluvial fans along the valley margins and the downvalley glacial limit during the Last Glacial Maximum (LGM). Alluvial fans from side tributaries create steep channel gradients and confine the river to a single-thread channel morphology with low sinuosity. The channel constrictions are preceded by low gradient meandering reaches, which show extensive lateral channel migration in response to a wide floodplain and the local base level control of the alluvial fans. Lower gradients near the glacial limit (about river mile 16) are likely caused by deep glacial scour during the Late Pleistocene and subsequent infilling with glacial and post-glacial sediment. In the lower 16 miles, channel gradient is steep and uniform, controlled by the base level of the Columbia River and in-channel bedrock as well as laterally by gravelly stream banks of glacial outwash terraces and high floodplain and terrace deposits that were determined to be 1,000-2,000 years old and 3,000-4,000 years old, respectively. While most of the channel characteristics are controlled by geologic features and formed by naturally occurring geomorphic processes, localized reaches within the study area do show channel changes that are associated with anthropogenic modifications such as channel straightening, levees, bank protection, and large woody debris and vegetation clearing. The channel changes are variable and include decreased sinuosity, increased stream gradient, channel incision, channel widening and bank undercutting. Reaches with these documented channel changes present the most opportunities to improve the quantity and quality of physical channel characteristics important for salmonids.

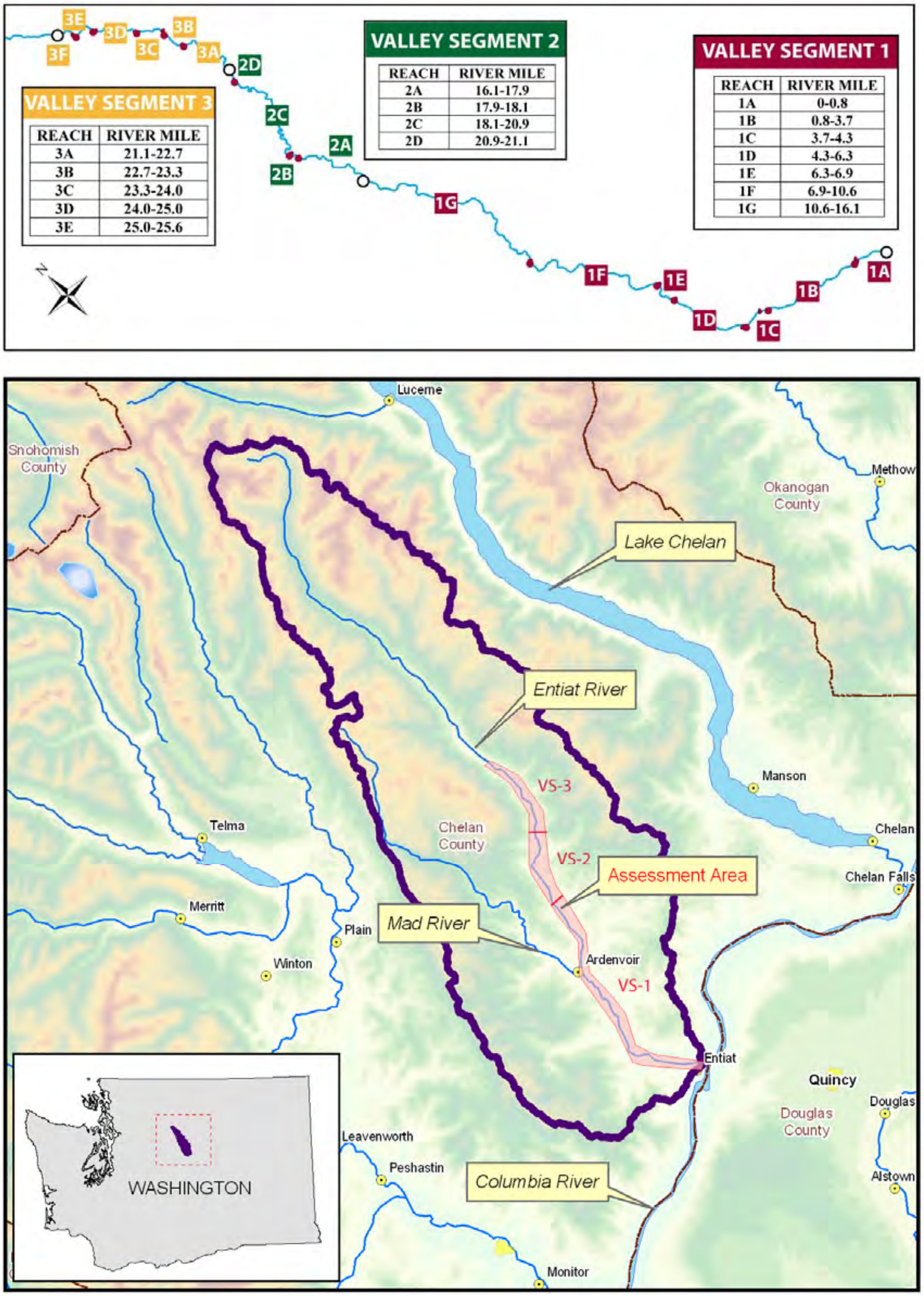
INTRODUCTION

Geomorphic data provide the physical basis for understanding how and where critical habitat for salmonids is formed along rivers. An understanding of physical river processes is necessary in order to implement habitat restoration actions that are compatible with the river processes and that will be sustainable in the long term. By understanding river processes, we can link the location of suitable habitat for salmonids with the physical characteristics of the system and explain why certain habitat features occur in some locations but not in others and whether it is likely that this type of habitat existed prior to human interaction with the river. The geomorphic data presented here were collected as part of a larger assessment along 26 miles of the Entiat River. The assessment used the geomorphic data along with hydraulic modeling and vegetation data to explain historical changes in the river system and to postulate potential causes for these changes. This provides an indication of whether channel processes have changed significantly during the historical period, thus impacting habitat the quality and/or quantity of habitat features.

The Entiat River drainage basin is located in western Chelan County, Washington. Runoff generated from the Entiat River drainage basin empties into the Columbia River just south of the city of Entiat (Figure 1). The headwaters of the Entiat River originate in the Cascade Mountains, and the topography of the basin varies significantly. The highest point is about 9200 feet, and the mouth of the Entiat River is at approximately 710 feet. The Mad River is the only major tributary of the Entiat River and ranges in elevation from 7000 to 1250 feet. The Entiat watershed is subject to frequent late spring and early summer snow-melt floods, which are major catalysts for channel change and the transport and redistribution of sediment in the river system. The “flood of record” occurred on May 29, 1948; the magnitude of this discharge was 10,800 cfs at the USGS gage near the mouth. Annual to 2-yr peak discharges are on the order of 1,000-3,400 cfs (Godaire et al. 2009), and act to modify in-channel features, such as channel bathymetry, bars and islands.

METHODS

The surficial geology of the Entiat River Valley was mapped at a scale of 1:6,000 using stereo images taken in 2002 by the U.S. Forest Service. Mapping was transferred into GIS by digitizing the lines drawn on aerial photography and then by comparing these contacts with light distance and ranging (LiDAR) data and inundation depths derived from the hydraulic modeling. Once units had been defined, soil descriptions were generated for the various units to provide an understanding of the depositional processes and to provide relative age information based on soil development. Soils were described using U.S. Department of Agriculture terminology from Birkeland (1999); sedimentological properties in the deposits were described using terminology from Boggs (1992). To obtain quantitative information about the age of the various deposits, charcoal samples were collected from the soils and submitted for macrobotanical identification. A subset of these samples was selected for AMS radiocarbon dating to determine their absolute age. Historical channels were mapped on rectified aerial photography by digitizing in GIS. They were then compared to LiDAR and 2006 aerial photography to determine if the locations of historical channels could be valid. Changes in historical channel sinuosity and planform were assessed and linked to known human modifications. Some alterations had already occurred before the earliest photograph; therefore, additional information was gathered from ground photography, flood management reports, and local accounts of river history.



VALLEY SEGMENT 3

REACH	RIVER MILE
3A	21.1-22.7
3B	22.7-23.3
3C	23.3-24.0
3D	24.0-25.0
3E	25.0-25.6

VALLEY SEGMENT 2

REACH	RIVER MILE
2A	16.1-17.9
2B	17.9-18.1
2C	18.1-20.9
2D	20.9-21.1

VALLEY SEGMENT 1

REACH	RIVER MILE
1A	0-0.8
1B	0.8-3.7
1C	3.7-4.3
1D	4.3-6.3
1E	6.3-6.9
1F	6.9-10.6
1G	10.6-16.1

Figure 1 Location map of Entiat River Basin (outlined in purple) and reach delineation within the study area (white dots show valley segment boundaries; purple dots show reach boundaries).

CHANNEL MORPHOLOGY

Channel morphology of the Entiat River is described based on channel gradient and channel planform (Figures 1 and 2). In order to describe channel morphology in detail, the 26 miles are divided into three valley segments, which are further subdivided into reaches within each valley segment. Valley segment 1 (VS-1) extends from RM 0-16.1 with its upper limit defined by the Potato Creek moraine at RM 16.1, which marks a change from the downstream high-gradient, dominantly single thread channel with low sinuosity meanders to the upstream low-gradient, multi-thread channel with predominantly high sinuosity meanders. The boundary between valley segments 2 (VS-2) and 3 (VS-3) at RM 21.1 is defined by a change in slope from the low-gradient meandering reach from RM 16.1 to 21.1 to a higher gradient segment upstream of RM 21.1. VS-3 retains a meandering channel but is more influenced by tributary alluvial fans that steepen and straighten the channel for short lengths.

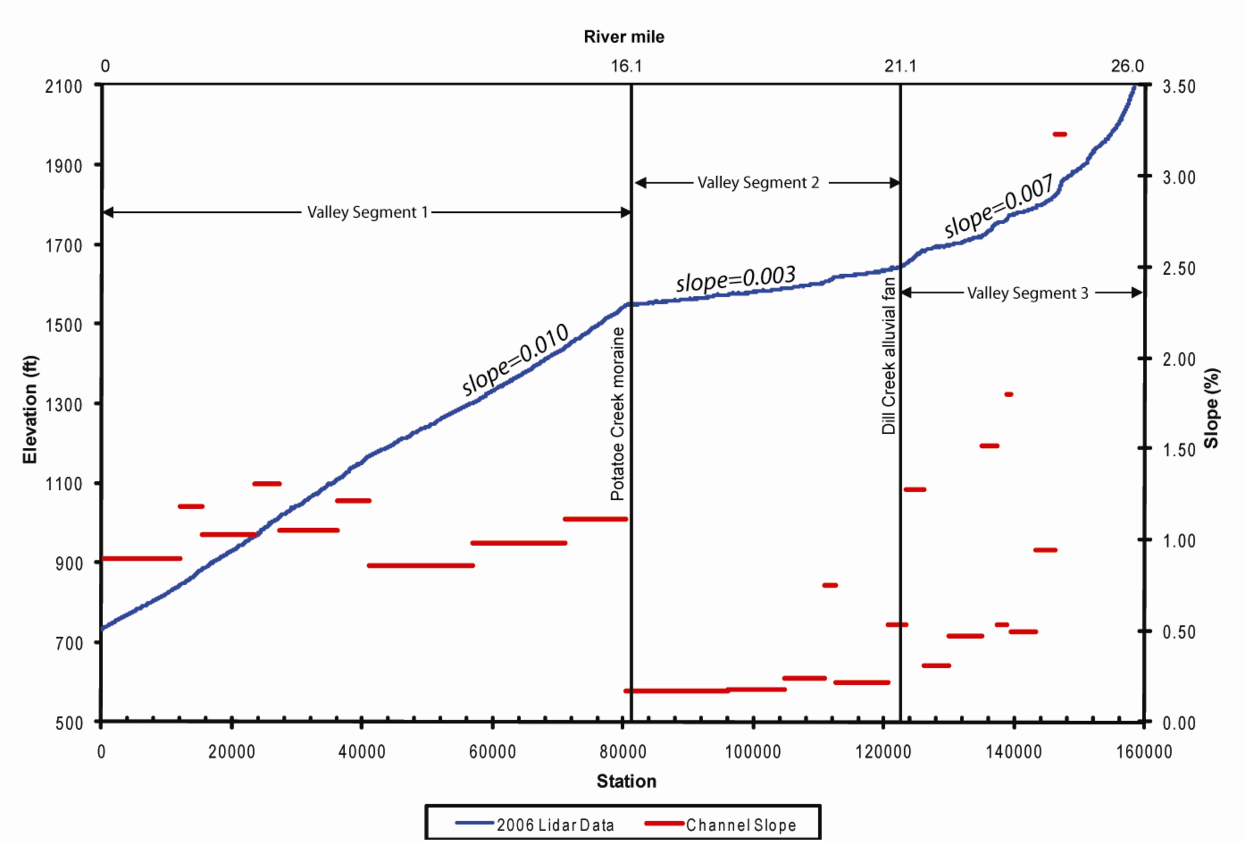


Figure 2 Longitudinal profile of the Entiat River from RM 0 to 26. Blue line shows elevation (ft).

Reaches are defined for each valley segment and reflect local changes in slope and channel planform. Three general reach types are defined for the study area: (1) single thread, high gradient-low sinuosity channel with a discontinuous, narrow to nonexistent active floodplain; (2) single thread to split flow, moderate sinuosity-high gradient channel with a discontinuous narrow to moderately wide active floodplain; and (3) multi-thread, high sinuosity-low gradient channel with a continuous, broad active floodplain. While these reach types exist throughout the study reach, they are predominant in certain valley segments. VS-1 contains reach types 1 and 2, while VS-2 and VS-3 contain mostly reach types 1 and 3.

SURFICIAL GEOLOGIC MAPPING

Surficial geologic units defined in this study are described on the basis of surface morphology, character of deposits, vertical and lateral relation to other mapped units, relative or absolute age, and geographic location (Table 1; Figure 3; Godaire et al. 2009).

Primary surficial deposits along the Entiat river include fluvial deposits, glacial deposits and alluvial fan deposits. Four fluvial map units are delineated and include the active channel, active floodplain, high floodplain and mid-Holocene terrace. The active channel (unit Qa4) is defined as "... the portion of a channel in which flow is present at the time of measurement, as opposed to the high-flow channel" (Neuendorf et al. 2005). In this case, the active channel also includes unvegetated sand bars that are modified on an annual basis by the largest flows during spring runoff. Deposits on the bars generally consist of a gravelly surface of pebbles and cobbles with underlying sandy sediments. Deposits in the channel are composed of unconsolidated sand with varying percentages of subangular to rounded boulders, cobbles and pebbles. The active floodplain (unit Qa3) has an irregular, low relief surface morphology with abundant overflow channels. Deposits can be composed of primarily sandy materials, gravelly sand or may have a thin cap of sandy sediments overly gravelly sand deposits. Flotsam deposited by historical floods can be observed in many places on the surface of this unit. The high floodplain (unit Qa2) is characterized by a planar surface morphology with localized irregular topography from relict channels. Portions of the surface may receive some overbank sedimentation from large floods in the present flow regime. Deposits underlying the high floodplain surface range from predominantly silty sand to a thin sandy cap of sediment over rounded cobbles and pebbles. The mid-Holocene terrace (unit Qa1) is characterized by a planar surface morphology with localized irregular topography caused by fallen trees or rockfall. Deposits that compose the terrace include moderate to well sorted silty sands that overlie alluvial fan sediments or fluvial gravelly sands.

Alluvial fan deposits (units Qaf1 and Qaf2) are prevalent in the Entiat Valley and are estimated to be Holocene in age. Surface morphology for most of the fans is relatively smooth presumably because relict bar and swale topography has been filled in by deposition of fine-grained sediments across the surface during smaller magnitude tributary events. Some of the larger fans upstream of RM 21 have irregular surface morphology where coarse deposits can still be observed at the surface. It is possible that these components are younger than the smoother fans or that these fans are composed of coarser material from steeper drainages than those downstream. Sediments that compose alluvial fans range from pebbly granitic sand to subangular to subrounded boulders and cobbles. Alluvial fan deposits are variable in height above the main Entiat River channel. In some cases, this unit is graded to the Entiat River and in other cases, it is elevated above the Entiat River, depositing sediment onto terrace surfaces or older alluvial fans.

Glacial outwash deposits (Qgo unit) represent the glacial outwash plain that was forming as the Entiat Valley glacier reached its maximum extent and began its recession. Terrace treads are distinct on the outer edges in most places and are mapped as Qgot. Materials that compose this unit are poorly sorted subangular to subrounded boulders and cobbles in a sandy matrix.

Table 1 Characteristics of surficial geologic units in the Entiat River valley.

Group	**Unit**	**Height above modern channel (ft)**	**Soil profile**	**Age (yrs)***
Floodplain and terrace deposits				
Qa4	Active channel	n/a	A/C	modern
Qa3	Active floodplain	<5	A/B/C	<500
Qa2	High floodplain	5-10	A/B/C	1,000-2,000
Qa1	Terrace	10-20	A/Bw/C	3,000-4,000
Glacial Deposits				
Qgo	Outwash terrace	~80	A/Bt/C	Late Pleist. to early Holocene
Qgot	Outwash terrace tread	variable	A/Bt/Bq	variable
Alluvial Fan Deposits				
Qaf2	younger fan alluvium	variable	A/C	<1,000
Qaf1	older fan alluvium	variable	A/Bw/C	1,000-4,000

*Ages derived from Puseman and Varney, 2009 and Godaire et al. 2009

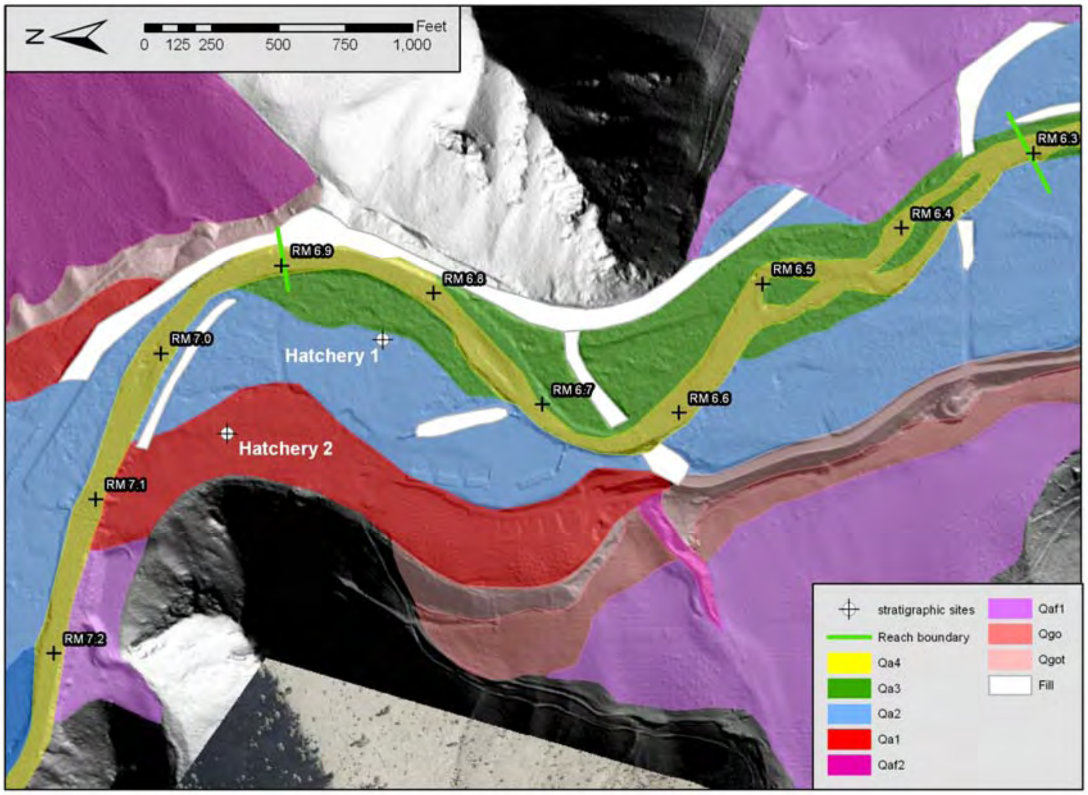


Figure 3 Example of surficial geologic mapping near Entiat River Hatchery, RM 6.3-7.2

HISTORICAL CHANGES IN CHANNEL MORPHOLOGY

The majority of historical channel changes in the Entiat Valley have occurred in VS-2 and VS-3, RM 16–26, where wide floodplain areas exist upstream of alluvial fan constrictions (Table 2). Channel migration in the reaches with wide floodplains is described as moderate or high, where the majority of channel positions have changed by more than one channel width in at least several locations within the reach between 1945 and 2006. Reaches with a low degree of change are reaches in which the majority of channel positions within the reach have not changed by more than one channel width between 1945 and 2006. In general, VS-1 (RM 0–16.1) is geologically constrained by alluvial fans, fluvial terraces and bedrock, so that little historical channel movement has occurred. One notable exception to this occurs in Reach 1C (RM 3.7–4.3), where a meandering channel existed in 1945. The channel was straightened along Reach 1C between 1945 and 1962, reducing channel sinuosity and eliminating the point bars and pools along meander bends. Since 1962, the channel has retained its straightened morphology. In VS-2 and VS-3, channel changes take the form of decreasing sinuosity and changes in planform from a multi-thread to a single-thread channel. For example, from RM 19.0–20.2, channel sinuosity decreased dramatically between 1945 to 2006 with the majority of change occurring between 1945 and 1962 (Figure 4).

Table 2 Historical channel changes, Entiat River study area

Valley segment	Reach	Reach type	Degree of change	Description	Sinuosity (2006) (ft/ft)	Change in Sinuosity (1945-2006) (ft/ft)
1 RM 0-16.1	1A	2	low	n/a	n/a	n/a
	1B	2	low	n/a	1.1	0.0
	1C	2	high	channelization	1.0	0.3
	1D	1	low	n/a	1.1	0.0
	1E	2	low	n/a	1.2	0.1
	1F	1	low	n/a	1.3	0.0
	1G	1	low	n/a	1.2	0.0
2 RM 16.1-21.1	2A	3	moderate	downstream meander migration; lateral migration	1.3	0.1
	2B	1	low	n/a	1.2	0.0
	2C	3	high	change in sinuosity and channel pattern	1.4	0.2
	2D	1	low	n/a	1.0	0.0
3 RM 21.1-26.0	3A	3	high	lateral migration; meander cutoffs	1.4	0.0
	3B	1	low	n/a	1.1	0.0
	3C	2	moderate	avulsion	1.1	0.0
	3D	3	high	change in sinuosity and channel pattern	1.2	0.2
	3E	1	low	n/a	1.2	0.0
	3F	3	moderate	avulsion	1.2	0.0

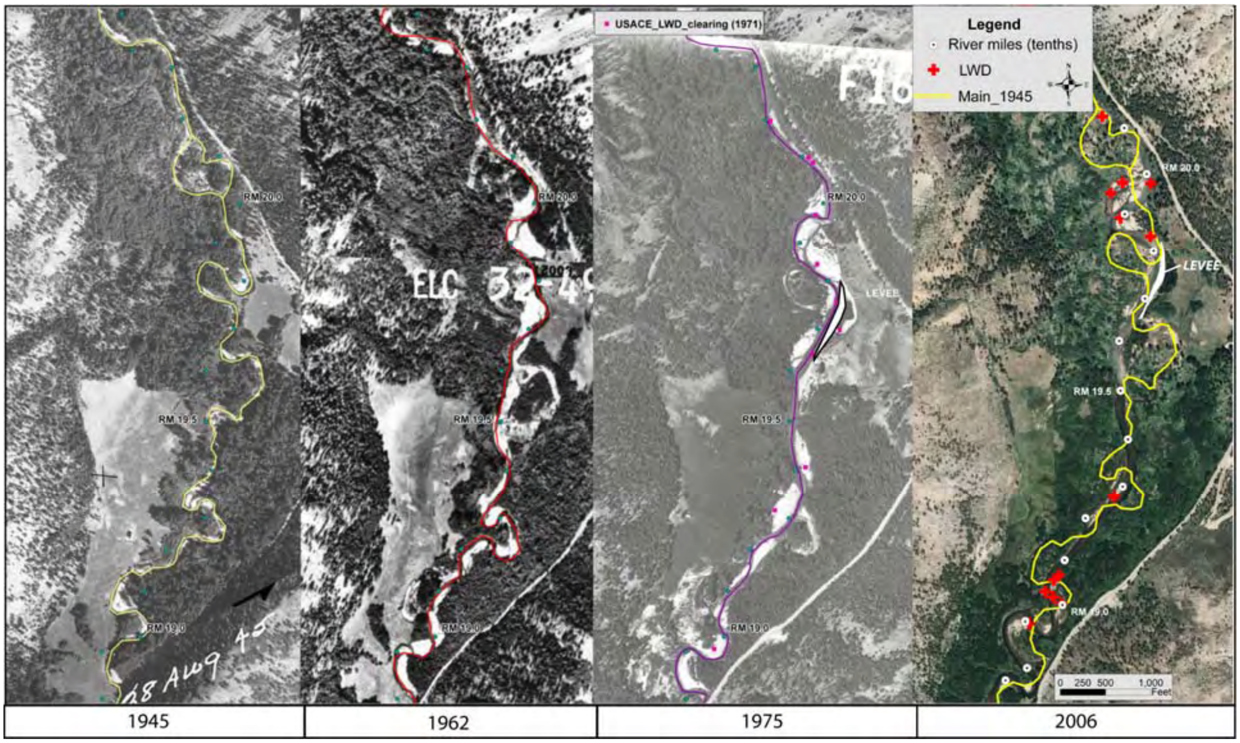


Figure 4 Example of historical channel change in Reach 2C, RM 19.0–20.2; 1945 channel centerline is overlaid on 2006 photography for comparison on far right.

It is likely that the 1948 flood was the catalyst for many of the avulsions that cutoff meandering sections of the 1945 channel in this reach. The construction of the dike along the left bank at RM 19.7 in 1973 along with large woody debris (LWD) clearing by the U.S. Army Corp of Engineers (ACOE) in 1971 may have also been factors in some changes from a sinuous meandering channel to a low-sinuosity straight channel between 1962 and 1975; however, many of the meander cutoffs occurred prior to these alterations. No evidence is available that documents any mechanical straightening of the channel in this reach between 1945 and 1962.

DISCUSSSION

Influence of geologic features on channel morphology The extent and character of geologic features provide information concerning controls on lateral and vertical channel movement over longer time frames than the historical period and many times are important factors in explaining variation in channel morphology along the length of a river corridor. Variations in channel planform and active floodplain extent can be linked to a combination of lateral and vertical geologic controls along the Entiat River. For instance, reaches with high sinuosity, multi-thread morphology and a continuous and extensive active floodplain lack geologic features such as alluvial fans, glacial outwash terraces, and older, gravelly stream terraces that limit the width of the floodplain (Figure 5). They are also influenced by grade control features, such as alluvial fans or glacial limits at their downstream ends, which cause low gradients and higher channel migration rates to persist within the reach. Reaches with low complexity and a narrow active floodplain typically have geologic features that are highly resistant to lateral erosion close to the active channel, such as coarse, gravelly alluvial fans, outwash terraces or bedrock. The coarse material issuing from these features exerts a vertical control as well on the channel bed, forcing the channel to maintain a steeper gradient than in other reaches (i.e, Woodsmith and Bookter, 2007; Godaire et al 2009). It is worth noting that the same geologic feature may have varying resistance depending on its composition in the subsurface. This is especially true for high floodplain areas that are located adjacent to the active floodplain. In VS-1, they are composed of gravelly materials and may provide greater resistance to lateral channel migration when compared to VS-2 and VS-3, where they are composed of greater amounts of sandy materials and are more readily eroded.

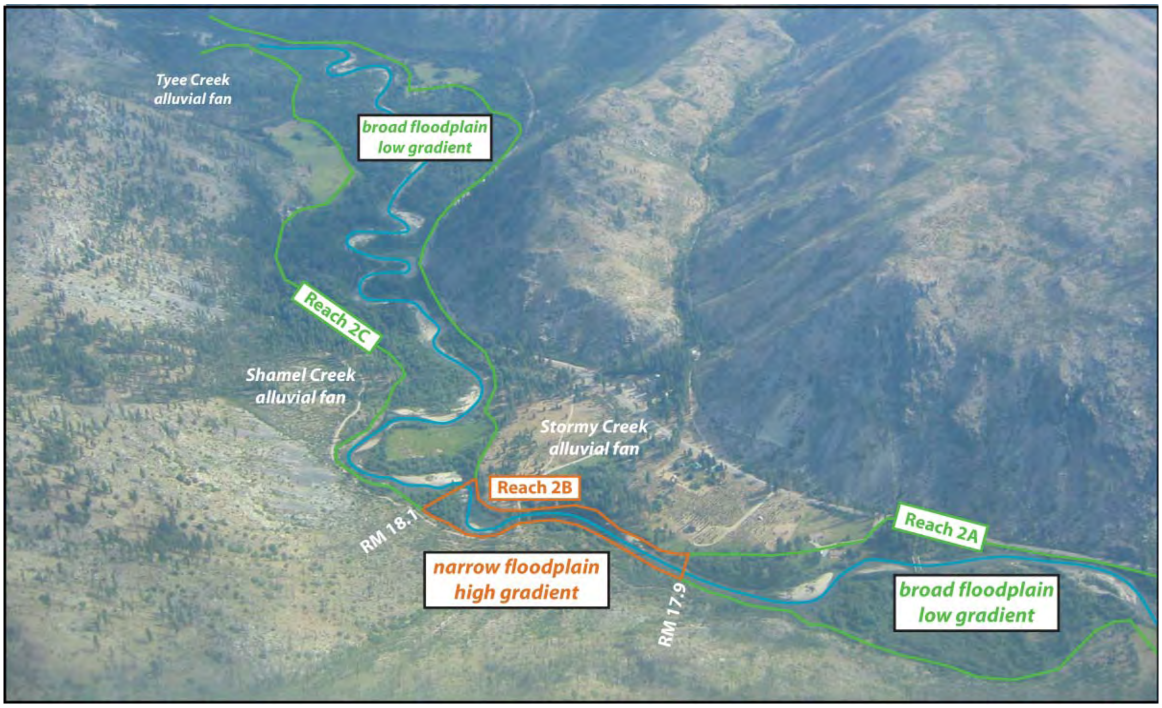


Figure 5 Example of the influence of geologic features, such as alluvial fans on channel morphology

Lateral changes: natural causes or human impacts? Linking the length of map units along the active channel with qualitative estimates of lateral channel migration shows that in VS-2 and VS-3, reaches with moderate to high rates of lateral migration also have a large proportion of active floodplain along the active channel (Figure 6). Thus, the lower slopes and presence of active floodplain in these reaches allow for substantial lateral migration and higher channel sinuosity. In most of these locations, the channel is eroding its active floodplain, which is a surface that would be expected to be reworked as the channel migrates across its floodplain. Reaches that have low rates of channel migration generally have steep slopes and minimal active floodplain along the active channel. In VS-1, the lateral historical channel migration rates are low. In most of these reaches, the active floodplain is relatively narrow and discontinuous. However, a few reaches have a high proportion of active floodplain along the active channel and still exhibit limited lateral migration. This suggests that factors in addition to bank resistance control the low rates of channel migration. It is likely that the steep slope and high stream power in addition to bank resistance naturally maintain a channel that is relatively narrow and carries high velocity flows. Human impacts may also play a role, however, in limiting lateral migration for some reaches in VS-1. Reach 1C exhibited a meandering channel planform in 1945, which was then mechanically straightened and continues to maintain its straight channel planform. In reaches 1B and 1E, active floodplain is adjacent to the active channel for at least half of the reach length; the presence of some small levees along the outer edge of the active floodplain suggests human features are at least in part responsible for the low rates of historical channel migration.

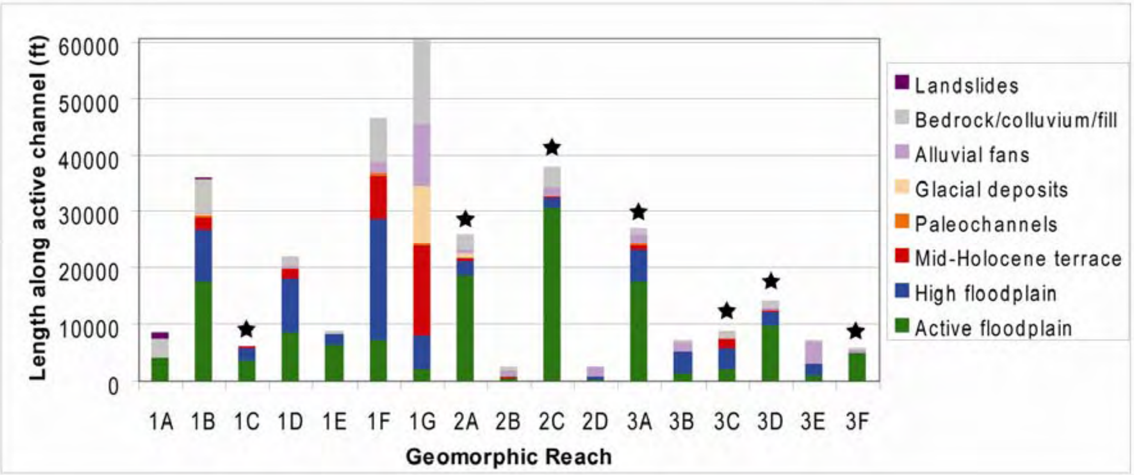


Figure 6. Length of map units along the active channel by reach; stars indicate moderate to high rates of historical channel change (from Table 3)

To further explore the role of human impacts versus natural processes on channel form, active channel and active floodplain widths are averaged by reach in order to identify general patterns as well as any deviations in width measurements that might signal altered areas. In general, width-averaged measurements show that wider active channels correspond to wider or unconfined active floodplains (Figure 7). Reaches with narrower or confined floodplains show channel widths that are very similar regardless of the width of the active floodplain. This would suggest that when in a confined state with relatively steep slopes, the channel trends toward an equilibrium width between 90 and 100 feet. Three reaches do not correspond to this general pattern; they include 1A, 1C, and 3C. In Reach 1A, backwater from Rocky Reach Dam creates an artificially wide channel where water ponds; thus, the active channel is much wider than the active floodplain. Reach 1C shows a narrower channel than any other reach; channel straightening is documented in this reach and suggests that it is artificially narrow and has probably incised to accommodate the narrower width. In Reach 3C, the active floodplain width is narrow despite the greater width of the active channel. In looking at this reach in greater detail, it was observed that a small section of the reach skews the average active channel width where a multithreaded channel exists. It should also be noted that Reach 3A has the widest active channel width, which is very similar to the active channel width in Reach 1A (as influenced by the backwater from Rocky Reach Dam). This implies that Reach 3A has an atypical active channel width, and may be caused by accelerated bank erosion in cleared areas.

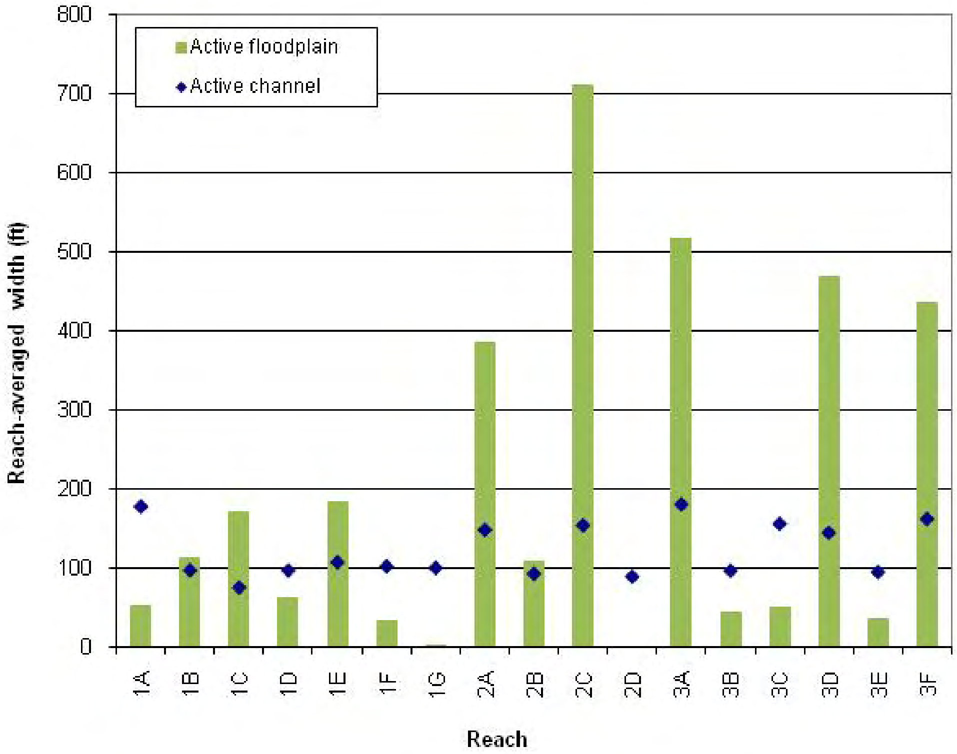


Figure 7. Reach-averaged widths, Entiat River study area

Implications for aquatic habitat and opportunities for protection or restoration Channel morphology along the Entiat River in the study area can be used to infer physical habitat availability for salmonids and to thus understand which reaches or areas are most suitable for restoration or protection of aquatic habitat. Channel complexity is considered to be a measure of habitat quality for salmonids and can be evaluated based on geomorphic characteristics. If a reach has a higher channel complexity, this would lead to a larger number of habitat features that could be utilized by salmonids. By the geologic history along a river system, we can evaluate whether the habitat features are predominantly limited by geologic or human features and thus whether they were present in similar or different amounts prior to the historical period.

In the 26-mile study area, greater channel complexity is associated with reaches that contain active floodplain areas, documented historical channel migration, side channels, large woody debris, and mobile sediment bars. These characteristics act to create a larger range of depths, velocities, and substrate suitable for a range of in-channel habitat and a greater number or length of side-channels suitable for off-channel habitat. Reaches without these parameters generally have lower channel complexity because their in-channel velocities, depths and substrates are more uniform and side-channel habitat is more limited. It would thus follow that greater opportunities for protection or restoration of diverse habitat such as pools, side channels, and backwater areas would be found in areas with greater channel complexity or in reaches with high potential for channel complexity if the reaches are impacted by human features. The reaches that were determined to have greater channel complexity and that have also been impacted by human modifications are 1B, 1C, 1E, 2A, 2C and 3A. Areas with low channel complexity present opportunities for the construction of in-channel features, but the creation of any off-channel features would be greatly limited by the extent of active floodplain existing in the reach.

CONCLUSIONS

Channel morphology on a broad scale is influenced by geologic features present in the lower 26 miles of the Entiat Valley rather than historically constructed features in the channel. This is illustrated by the change in stream gradient at geologic features, the presence of alluvial surfaces that are 1,000 years or older adjacent to the stream channel and the lack of channel migration near landforms that confine the river and extensive migration upstream of these features, which act as a local base level control. Channel migration between 1945 and 2006 has occurred in multiple locations in the assessment area. In most of these locations, the channel is eroding its active floodplain, which is a surface that would be expected to be reworked as the channel migrates across its floodplain. Several reaches do show evidence of human impacts which include levee construction, channel straightening and clearing of vegetation and large woody debris; these impacts are generally restricted to localized areas and are not responsible for the overarching channel morphology along the length of the river. This study demonstrates that a geomorphic approach can resolve differences in channel planform and character that are due to natural geologic constraints and processes versus human impacts. This understanding can be used to identify areas, both relatively unimpacted and impacted, that could be pursued to protect or enhance aquatic habitat.

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