MORPHOLOGY OF SMALL, DISCONTINUOUS MONTANE MEADOW STREAMS IN THE SIERRA NEVADA

A thesis submitted to the faculty of
San Francisco State University
In partial fulfillment of
The requirements for
The degree

Master of Arts
in
Geography: Resource Management and Environmental Planning

by

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San Francisco, California

December 2012

CERTIFICATION OF APPROVAL

I certify that I have read *Morphology Of Small, Discontinuous Montane Meadow Streams In The Sierra Nevada* by Michelle Laura Slocombe, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirements for the degree: Master of Arts in Geography: Resource Management and Environmental Planning at San Francisco State University.

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MORPHOLOGY OF SMALL, DISCONTINUOUS MONTANE MEADOW STREAMS IN THE SIERRA NEVADA

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2012

Various fluvial geomorphic models have been developed to characterize the relationships between planform and bedform features of large alluvial channels; however, little information exists for meadow channel morphology. Field investigation of seven narrow, low-energy meadow stream reaches in the northern Sierra Nevada range of California revealed similarities and differences to larger alluvial channels. The average radius of curvature to channel width ratio (5.54) of the meadow streams was almost double that of larger alluvial streams (3.1), with a standard deviation of 4.66. Average meander wavelength to channel width ratio (22.43) was almost triple that of typical alluvial streams (8.5), with a standard deviation of 16.80. Bedform features occurred at an average of 6.72 channel widths, similar to typical pool-riffle spacing of 5-7 channel widths. Grass sod connected a series of scour pools, providing the same energy drop function as riffles or steps. Results suggest that bedform regularity is similar to typical pool-riffle systems but planform features are less developed. Restoration efforts can benefit from considering how planform and bedform channel patterns develop in these meadows.

I certify that the Abstract is a correct representation of the content of this thesis.

__________________________________ __________________

Chair, Thesis Committee Date

ACKNOWLEDGEMENTS

This research would not have been possible without the knowledge and resources of the following groups and individuals: Terry Benoit and Leslie Mink with the Feather River Coordinated Resource Management Group for their recommendations of potential study sites in the northern Sierra Nevada; Randy Westmoreland of the U.S. Forest Service for his indispensable knowledge about meadow restorations and the history of Carman Valley; fellow San Francisco State University geography friends and colleagues for their valuable advice and suggestions; Adam Davis for generously volunteering his time to help with field work; Marilyn Hope Smulyan for her assistance during field work and positive attitude during hours of surveying; my husband, Andrew Slocombe, for cheerfully accompanying me in the field and providing feedback on early drafts; Andrew Oliphant for his insightful comments and questions during each stage of research; and Jerry Davis for introducing me to this topic and for guiding me through the thesis process with enthusiasm and boundless energy.

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1. Introduction

Montane meadows in the Sierra Nevada mountain range of California are unique riparian wetland ecosystems where seasonal fluctuations in water saturation provide rich environments for biota at elevations between 600-3,500 m (Rundel et al., 1977). Meadows are the foundations for healthy ecosystems and when they are altered, the effects reverberate throughout the biosphere. Meadows attenuate peak flood flows, filter sediment, and increase water storage capacity, allowing plant and wildlife populations to thrive (Ratliff, 1982). In the Sierra Nevada, wet meadows are inextricably linked to a shallow groundwater table, which drives productive and diverse ecosystems despite the characteristically dry summer season (Loheide et al., 2008). These meadows represent less than 1% of the Sierra Nevada landscape, but nevertheless support more biodiversity than any other habitat type (Kattelmann and Embury, 1996).

The interconnections between hydrology, vegetation, and stream geomorphology create unique ecological conditions that make meadows prime biological habitats. Sierra Nevada meadow streams contribute to the stability of the broader landscape by providing a foundation for physical integrity. Of direct importance to humans, Sierra meadow streams play a vital role in ensuring the quality and availability of freshwater to the populous Central Valley and San Francisco Bay Area (Pupacko, 1993). Meadow environments regulate the snowmelt-driven hydrologic regime and help filter sediment. With millions of people directly dependent on freshwater from the Sierra Nevada, understanding the geomorphology of meadow streams should be a priority for land managers. Despite the highly valuable role of meadow streams, little information exists regarding their status and geomorphology.

Stream geomorphology includes planform features, such as meander curves, and bedform features, such as pools and riffles. Changes in planform morphology can have significant effects throughout an entire stream system, including sensitive riparian zones. Bedform features are part of the channel bottom and help dissipate energy (Leopold et al.. 1964; Langbein and Leopold, 1966; Yang, 1971) while providing stable spawning and rearing habitat for fish and other aquatic organisms (Gregory et al., 1994; Gurnell and Sweet, 1998). The majority of stream geomorphology principles refer to larger alluvial channels while only limited research is available to characterize small, discontinuous meadow channels (Hagberg, 1995; Jurmu and Andrle, 1997; Jurmu, 2002; Purdy and Moyle, 2006).

Recent work has shown that wetland stream morphology tends to diverge from typical alluvial stream characteristics. For example, wetland streams in the Midwest and East Coast of the United States contained tighter bends, larger wavelength-to-width ratios, lengthier straight reaches, greater channel width at riffles, and a more unusual thalweg pattern (Jurmu and Andrle, 1997). Pool-riffle locations were more inconsistent due to the low energy gradient in wetland environments (Jurmu, 2002). Watters and Stanley (2007) found that peatland channels had lower width-to-depth ratios and longer straight reaches than streams in typical alluvial settings.

As the value of meadow habitats are better understood, interest in restoration projects is becoming increasingly common in the Sierra Nevada (Purdy and Moyle, 2006). However, minimal information for meadow stream morphology is incorporated into restoration and monitoring plans, reflecting the assumption that meadow streams are similar to alluvial streams (Jurmu and Andrle, 1997; Jurmu, 2002; Purdy and Moyle, 2006). This research addresses a critical data gap by investigating the mechanisms underlying small, discontinuous channels common to the Sierra Nevada montane zone.

The purpose of this research is to identify and characterize planform and bedform morphological features of small, discontinuous montane meadow stream channels in the northern Sierra Nevada. These features were compared to morphological models of alluvial channels as found in the literature. Analysis of channel planform characteristics included radius of curvature, meander wavelength, and straight reaches. Channel bedform analysis included pool-riffle spacing and pool-formation mechanisms together with an examination of discontinuous channel morphology. This comparison of morphological features provides evidence for how Sierra Nevada meadow streams compare to larger alluvial channels. Results from this study will provide land managers with better information to develop custom restoration and monitoring plans for meadow streams, taking into account the unique environmental factors acting on these channels.

1.1 Physical Setting

The Sierra Nevada mountain range in northern California is composed of steep valleys interspersed with shallow alluvial basins of extinct lakes. Today, many alluvial valleys have developed into meadows, constituting the most biologically active plant communities in the Sierra Nevada (Ratliff, 1982). This region typically receives the majority of precipitation in the winter months, with a mean annual rainfall of ~1,092 mm (Rundel et al., 1977). Most of this precipitation falls as snow during the winter, with peak flows corresponding to peak snowmelt in April and May. Summer months are characteristically dry for the Mediterranean climate. During the snowmelt season, overland flow dominates the entire meadow surface while subsurface drainage takes over during the dry summer months. Meadow sod tends to be erosion-resistant due to the dominance of hydric and mesic vegetation such as sedges (*Carex spp.*) and rushes (*Juncus spp.*). Xeric vegetation communities, including sagebrush (*Artemisia tridentata*), are present in areas where the groundwater table is low.

Northern Sierra Nevada meadows are characterized by the presence of shallow, heavily vegetated stream channels that are almost indistinct, particularly when vegetation is thick during the summer months (Hagberg, 1995). In place of the classic gravel-bed entrenched channels typical of the West, a key distinguishing feature of these meadow channels is the presence of a series of scour pools connected by grass sod. The resistant grass sod serves a similar energy-drop function as riffles or steps in typical alluvial systems (Figure 1). This research should provide better clarity for this unique geomorphic feature.

Figure 1. Instead of riffles composed of coarse sediment, the meadow channels exhibited "grass riffles", or stretches of grass sod connecting two scour holes, as seen in this photograph of Carman Creek in Three Corner Meadow. Gray arrow indicates direction of water flow during the wet season.

1.1.1 Regional Land-Use History

Meadows are the most sensitive landforms in Sierra Nevada watersheds and are highly impacted by grazing, logging, and other anthropogenic activities, many of which are still widely felt. From the mid-1800s to the early 1900s, Sierra meadows were severely affected due to the arrival of European settlers and their associated land-use practices (Ratliff, 1985; Allen-Diaz et al., 1999). Stream incision and the resulting transition from hydric to xeric vegetation eliminated wide swathes of riparian habitat (Ratliff, 1985). As the environmental benefits of meadows are increasingly recognized, restoration projects are becoming more common in this region (Purdy and Moyle, 2006).

Carman Creek, located in the Feather River watershed in the Tahoe National Forest, is a recently restored meadow stream and provides an example of the important biological and hydrologic value of meadow restorations. The stream runs through a series of cascading montane meadows in Carman Valley, including Knuthson Meadow and Three Corner Meadow, and was identified as an impaired ecosystem in the 1950s due to railroad logging and grazing (Sierra Valley Resource Conservation District, 2004). Channel incision caused the meadow system to dry out, with vegetation succession from mesic to xeric species (Figure 2) (Sierra Valley Resource Conservation District, 2004). The entrenched gully cut off regular streamflow to the floodplain causing significant lowering of the water table and loss of water storage capability. In 2001, federal and local agencies restored Carman Creek using the "pond-and-plug" technique, which involved filling the incised ditch and allowing the stream to spread out onto the meadow surface into its natural remnant channels (Figure 3). The restoration was successful in reestablishing proper hydrologic function and biological habitat throughout Carman Valley (Sierra Valley Resource Conservation District, 2004). This case study provides a representative example of the history of many Sierra meadow streams and highlights the ecological value of restoration.

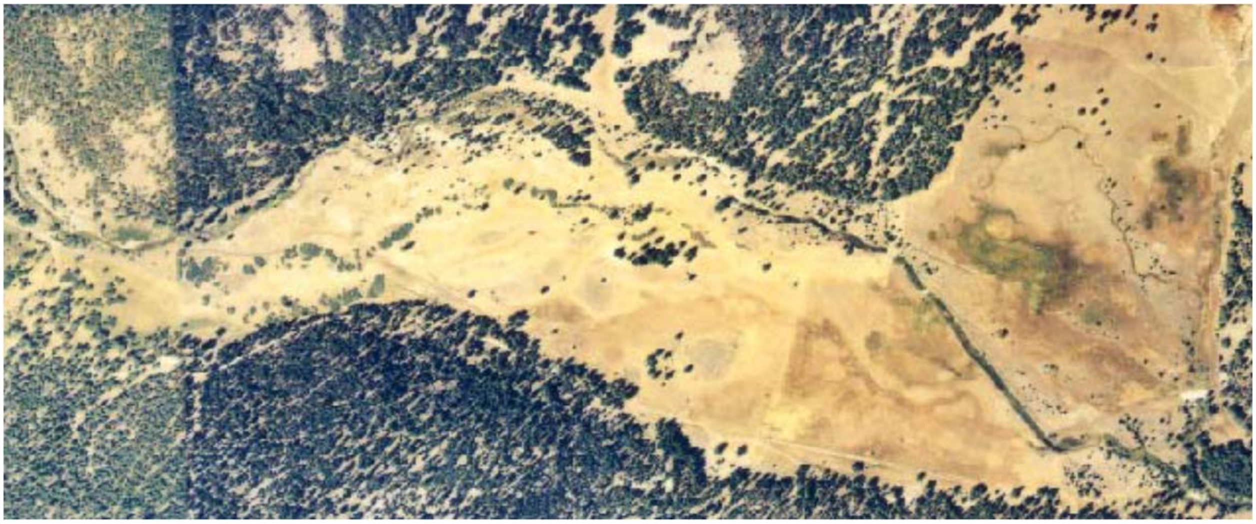


Figure 2. Aerial view of Knuthson Meadow pre-restoration. The incised channel can be seen as a straight line cutting across the meadow on the right (Sierra Valley Resource Conservation District, 2004).

Figure 3. Aerial view of Knuthson Meadow post-restoration. The ponds created by the restoration are located where the incised channel used to be and multiple natural channels are visible on the meadow surface (Sierra Valley Resource Conservation District, 2004).

1.1.2 Study Site Descriptions

Four stream reaches were selected along Carman Creek, two reaches in Three Corner Meadow and two reaches in Knuthson Meadow. To increase the sample set, three additional reaches within the Feather River watershed were selected: Willow Creek, Haskell Creek, and Rowland Creek, for a total of seven reaches (Figure 4).

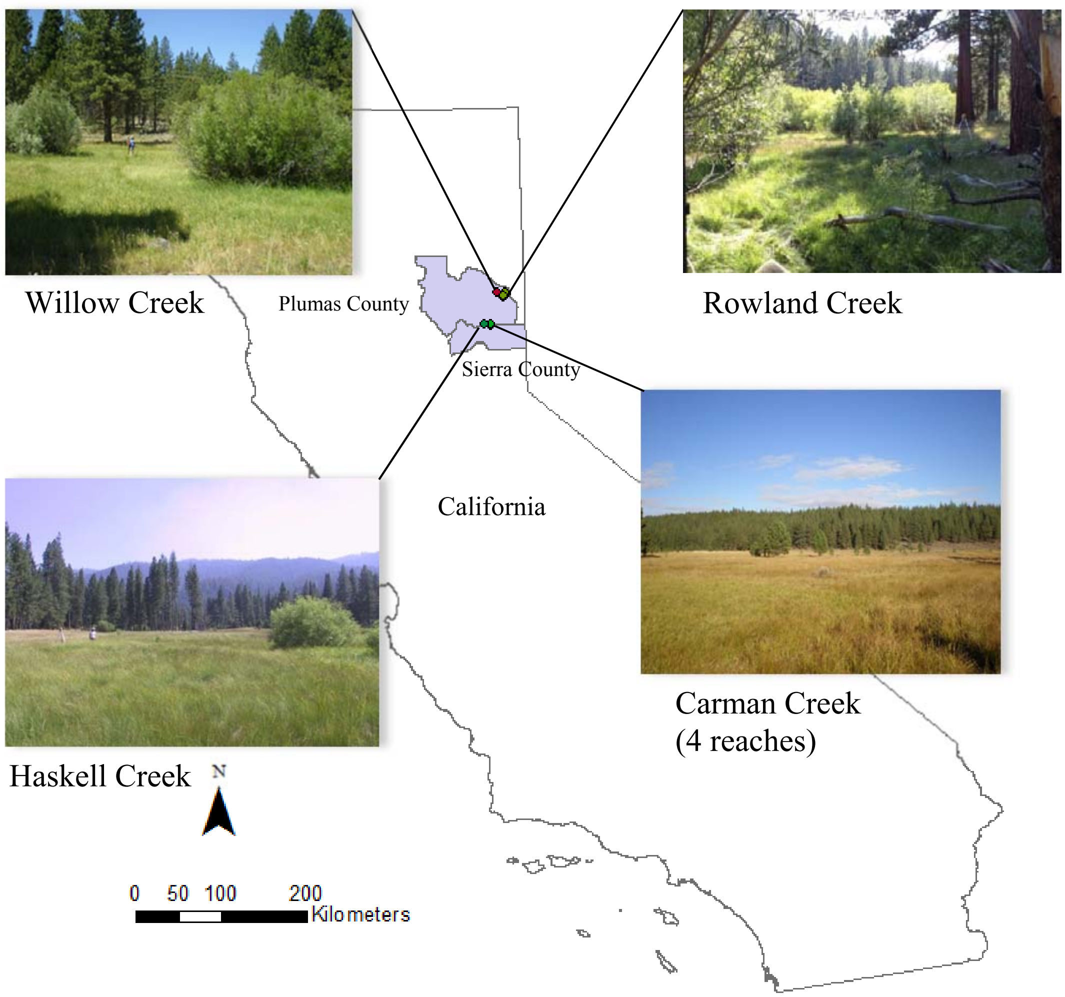


Figure 4. Map of California showing study site locations and photos of meadow sites.

Five reaches were located in restored systems; two reaches in natural systems. Study sites were selected to document a range of conditions under which the grass riffle energy-drop phenomenon occurs. Physical characteristics are summarized for each stream reach in Table 1.

Table 1 Summary of physical characteristics of study reaches

Stream Reach	*Elev. (m)*	*Watershed Area (km^2)*	*Stream Flow*	*Restoration Status*
Carman Creek North Fork – Knuthson Meadow	1,520	30	Seasonal	Restored
Carman Creek South Fork – Knuthson Meadow	1,520	30	Seasonal	Restored
Carman Creek Upper – Three Corner Meadow	1,530	16	Seasonal	Restored
Carman Creek Lower – Three Corner Meadow	1,530	16	Seasonal	Restored
Willow Creek	1,808	17	Seasonal	Unrestored
Haskell Creek	1,384	11	Perennial	Restored
Rowland Creek	1,937	48	Perennial	Unrestored

All sites were chosen based on recommendations from restoration geomorphologists with the Feather River Coordinated Resource Management and the U.S. Forest Service. Site selection was further refined based on the following criteria:

- Location in a montane meadow (600 m – 3,500 m elevation)
- Small drainage area (less than 50 km^2)
- Narrow, discontinuous stream channel comprising a series of scour holes connected by grass and sod

2. Materials and Methods

2.1 Field Methods

We used level surveying and GPS technologies to identify and measure planform and bedform features. Our method emphasized obtaining a sufficient number of points to accurately capture the spatial resolution of the stream features with respect to the research question. For example, the density of survey points was increased in areas of greater sinuosity or the presence of features of interest.

Longitudinal profiles and channel cross-sections were surveyed based on standard leveling techniques described by Harrelson et al. (1994), including establishment and proper referencing of benchmarks and comprehensive note-taking and field sketches. Survey benchmarks were established on permanent features such as piezometers, fence stakes, and tree trunks. A Topcon laser level and rod-mounted receiver were used to capture the relative elevations of survey points. We surveyed each point along the thalweg at approximately 1.5 m intervals, with cross-sections measured at approximately 3.0 m intervals. To minimize errors or inconsistencies in manual data recording, two people confirmed the rod readings and all measurements were repeated verbally. Measurements were read directly off the rod and recorded to the nearest millimeter.

In addition to the laser level elevation readings, a GeoXH GPS unit acquired x, y, z coordinates for each point. GPS accuracy after differential correction is shown in Table 2.

Table 2 Summary of GPS accuracy after differential correction from Trimble Pathfinder software

GPS accuracy after differential correction	Knuthson Meadow	Three Corner Meadow	Willow Creek	Haskell Creek	Rowland Creek
0-15 cm	95.64%	14.19%	27.26%	96.70%	85.97%
15-30 cm	4.19%	8.53%	8.47%	-	4.63%
30-50 cm	0.16%	14.78%	15.05%	0.02%	7.17%
0.5-1 m	0.01%	30.38%	29.39%	1.46%	1.54%
1-2 m	-	19.01%	14.27%	1.75%	0.22%
2-5 m	-	11.09%	5.08%	0.07%	0.46%
>5 m	-	2.02%	0.48%	-	-
# of corrected positions	7,669	5,744	2,916	4,582	3,237

The same points surveyed with the laser level were also surveyed with the GPS unit. Station distances between successive points were recorded on a 100 m measuring tape laid out along the channel. This method posed some difficulties in the perennial streams where water flow altered the position of the tape, but was more accurate and efficient than using a laser rangefinder.

One of the main challenges was locating the seasonal stream channels due to lack of distinct banks and the presence of extensive vegetation (Figure 5).

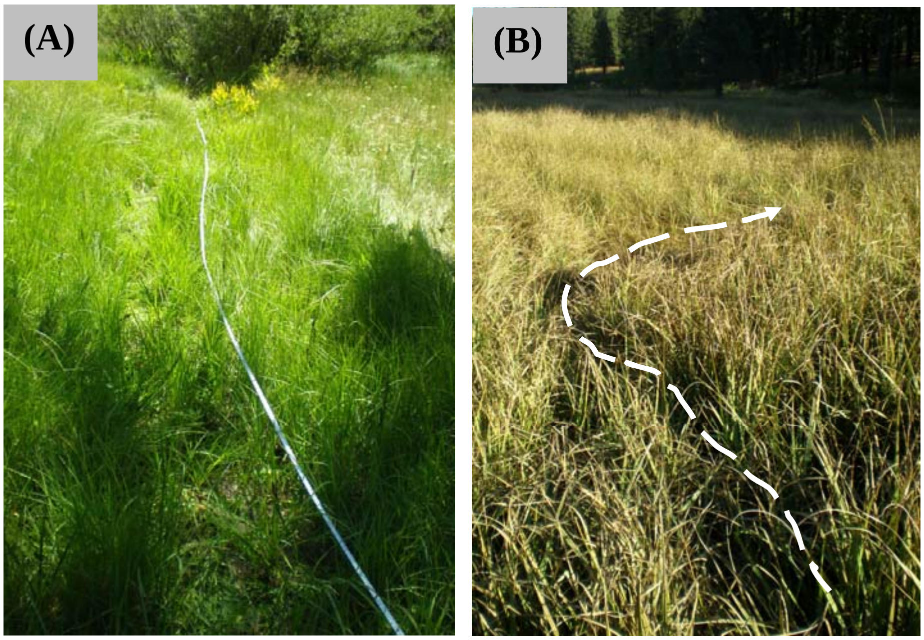


Figure 5. Examples of small, indistinct meadow stream channels observed during the dry season. (A) The white measuring tape marks the location of the channel in Willow Creek. (B) The dashed white line indicates the location of the channel in the Knuthson Meadow reach of Carman Creek.

We addressed this problem by surveying cross-sections to find the lowest point, then following the low points to survey a longitudinal profile. Vegetation and sediment signals (such as the transition from vegetation to bare ground) also helped locate the channel. The indistinct channels posed challenges for defining bankfull width. This is a critical variable but can be problematic to define in wetlands due to the absence of clearly defined terraces, presence of surface water beyond the channel, and high permeability of channel banks (Jurmu and Andrle, 1997; Watters and Stanley, 2007). Several wetland researchers have simply determined their own definition of bankfull width based on local variables, particularly vegetation characteristics (Jurmu and Andrle, 1997; Watters and

Stanley, 2007). For this study, bankfull width was measured with a survey tape and was judged by evaluating changes in topography (i.e. a break in slope) and vegetation (i.e. from bare surfaces to vegetation). Where the discontinuous nature of the stream reaches prevented the identification of bankfull, those widths were labeled “indistinct”.

2.2 Analysis and Comparison of Geomorphic Features

ArcGIS was used to delineate channel outlines and calculate planform measurements such as radius of curvature, straight reach length, and meander wavelengths. The bedform differencing technique (O’Neill and Abrahams, 1984) was used to objectively identify the number and distribution of pools and riffles in each reach. A pool-riffle sequence was defined as any consecutive pool *and* riffle, or vice versa. Bedforms were defined as either a pool *or* a riffle. The bedform differencing technique involves identifying a set tolerance value (T) based on the standard deviation (S_D) of elevation differences of the longitudinal profile. Where the cumulative elevation change since the last bedform exceeds T, the local minima or maxima is identified as the riffle crest or pool trough (O’Neill and Abrahams, 1984). A range of T-values between $0.25S_D$ and $1.0S_D$ were tested for each study reach but it was found that T-values between $0.50S_D$ to $0.75S_D$ most closely approximated field observations for bedform locations.

3. Results and Discussion:

Key morphological features were measured for each stream reach and summarized in Table 3.

Table 3 Comparison of morphological data collected for study reaches

Stream Characteristics	***Carman Creek North Fork - Knuthson***	***Carman Creek South Fork - Knuthson***	***Carman Creek Upper - TCM***	***Carman Creek Lower -TCM***	***Willow Creek***	***Haskell Creek***	***Rowland Creek***
Sinuosity (*P*)	1.09	1.17	1.02	1.07	1.14	1.45	1.39
Average channel width (w) (m)	1.21	1.47	1.65	1.40	1.41	0.48	0.83
Average water depth (d) (m)	n/a	n/a	n/a	n/a	n/a	0.256	0.176
Average slope	0.0107	0.0119	0.0123	0.0107	0.0281	0.0305	0.0266
Mean radius of curvature (r_m) (m)	8.52	10.75	1.77	2.40	7.51	5.46	4.09
Mean radius of curvature/channel width (r_m/w)	7.04	7.31	1.07	1.72	5.33	11.38	4.93
Average meander wavelength (l) (m)	33.34	28.28	5.81	5.03	41.00	20.31	25.10
Meander length/channel width (l/w)	27.55	19.24	3.52	3.59	29.08	42.31	30.24
Study reach length, thalweg (m)	268.65	272.73	42.01	66.4	149.9	135.30	99.6
Longest straight reach (m)	44.96	50.47	16.91	10.68	12.57	9.9	12.44
Straight reach length/channel width (l_s/w)	37.16	34.33	25.46	7.63	8.91	20.63	14.99
T-value (bedform differencing)	0.75	0.75	0.75	0.75	0.50	0.50	0.50
# of bedforms identified in each reach	38	39	14	17	33	20	12
Pool-riffle spacing/channel width	41.94	84.39	7.7	22.19	26.56	93.77	30.04
Bedform spacing/channel width	6.62	4.33	3.30	7.83	3.22	11.72	10.01

These values were then compared to the morphological features as defined in the literature and summarized in Table 4:

Table 4 Morphological models of alluvial streams cited in the literature

Morphology	***Morphological Feature***	***Source***
Planform	Mean radius of curvature to width (r_m/w) between 2 and 3	Leopold and Wolman (1960); Hickin (1974); Williams (1986)
	Meander wavelength to width (l/w) ratio between 7 and 10	Leopold et al. (1964)
	Straight reach to width ratio (l_s/w) doesn't exceed 10 channel widths	Leopold and Wolman (1957)
Bedform	Pool-riffle spacing between 5-7 channel widths	Leopold et al. (1964); Keller (1972); Keller and Melhorn (1978)
	Similarity to discontinuous gullies/channels	Leopold and Miller (1956)

3.1 Planform Characteristics

Fundamental empirical principles for channel planform morphology include the relationships between meander length, channel width, and radius of curvature (Figure 6).

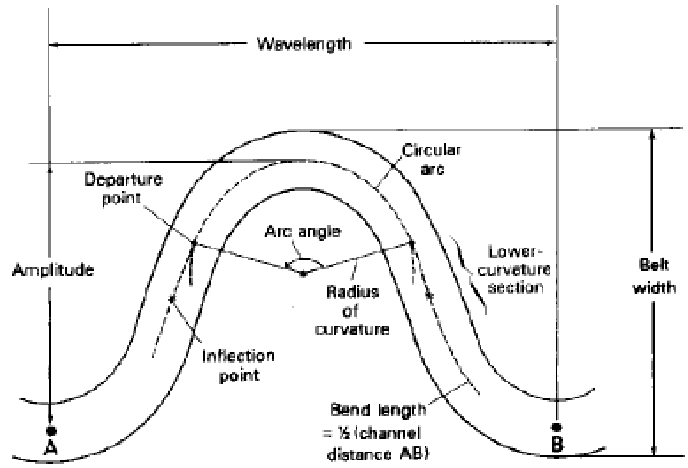


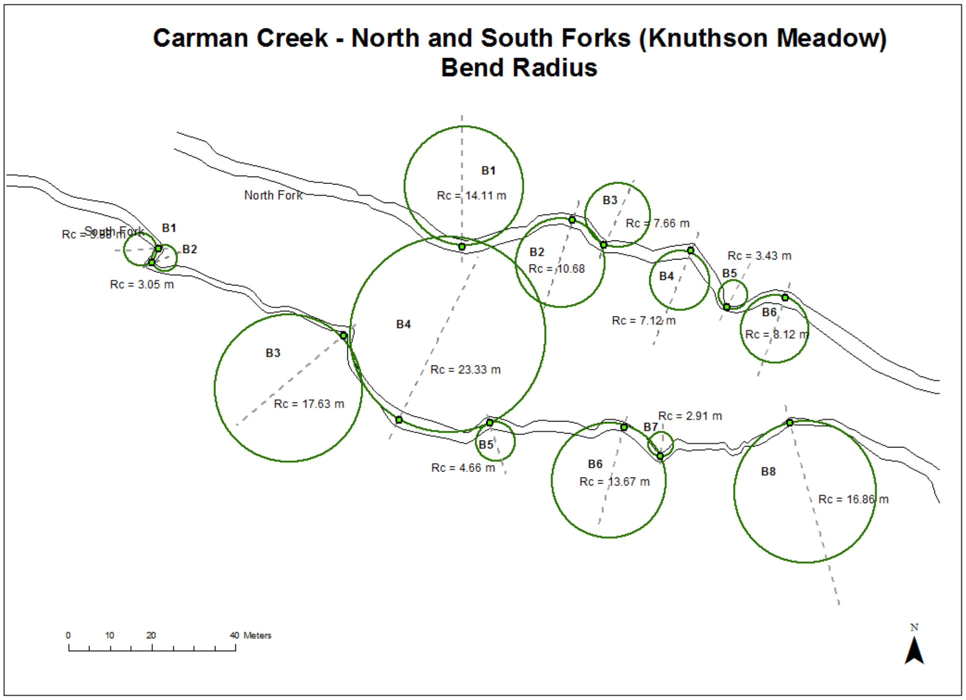
Figure 6. Diagram illustrating radius of curvature, channel width, and channel axis (Williams, 1978, p.148).

Planform types are distinguished by degrees of sinuosity (*P*), defined as the ratio of channel length to valley length (L_c/L_v) or valley slope to channel slope (S_v/S_c) (Schumm, 1985). *P*-values can range from 1.0 (straight) to approximately 3.0 (highly sinuous), depending on factors contributing to channel stability, such as vegetation or substrate (Schumm, 1985). Streams with a *P*-value greater than 1.5 are considered meandering (Jurmu, 2002). The *P*-values for the study streams range from 1.02 to 1.45, and are not considered meandering.

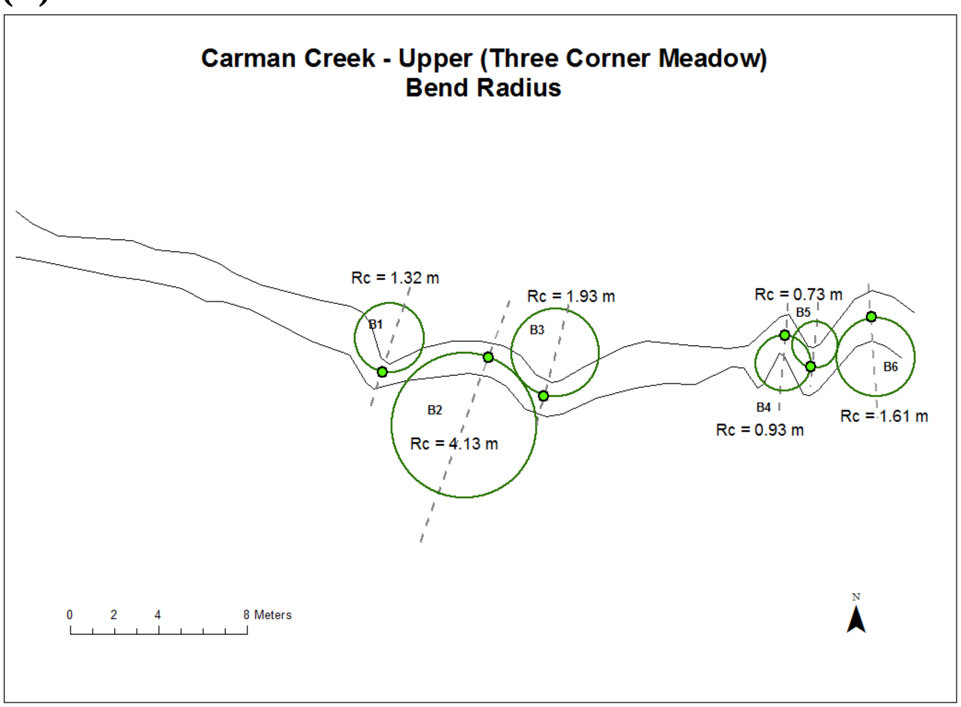
3.1.1 Radius of Curvature

Leopold and Wolman (1960) concluded that, regardless of river size, the ratio of mean radius of curvature to width (r_m/w) is generally between 2 and 3. Hickin (1974) and Williams (1986) found that values for r_m/w agreed with the results of Leopold and Wolman (1960) for perennial alluvial streams worldwide. Radius of curvature (r_c) for each study reach bend was calculated based on the following equation: $R_c = C^2/8M + M/2$, where C = chord length and M = middle ordinate distance. Bend radii are depicted by circles in Figure 7. The selection of bends in these reaches was subjective due to the indistinct nature of the meanders combined with the low sinuosity values.

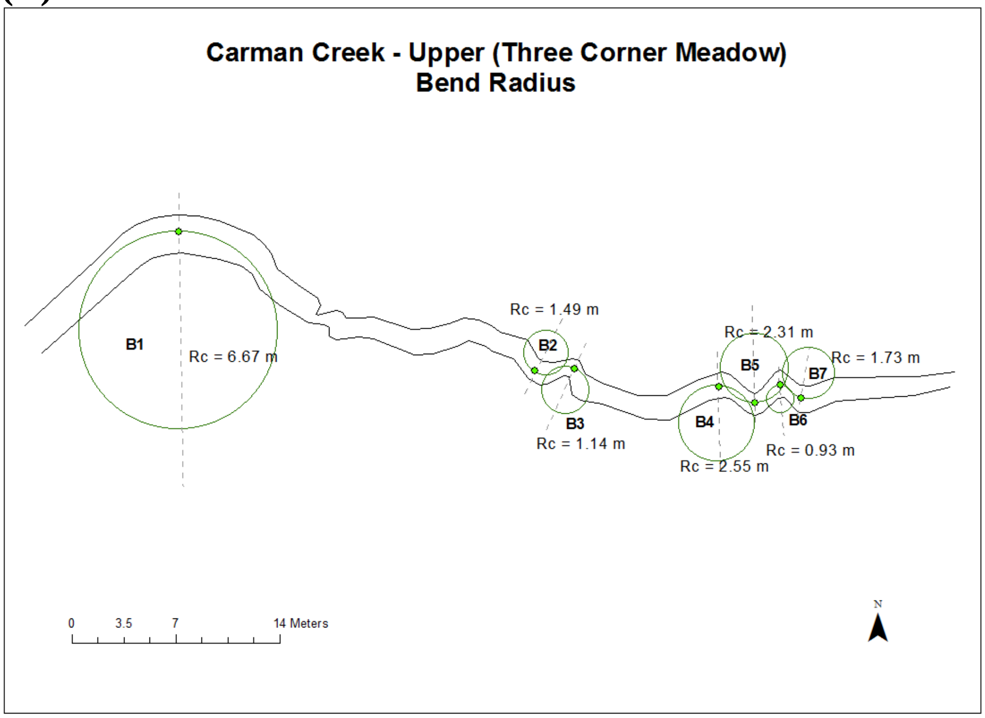
(A)


Carman Creek - North and South Forks (Knuthson Meadow)
Bend Radius
North Fork
South Fork
B1
B2
Rc = 3.05 m
B1
Rc = 14.11 m
B3
Rc = 7.66 m
B2
Rc = 10.68
Rc = 3.43 m
B5
B4
Rc = 7.12 m
B6
Rc = 8.12 m
B4
Rc = 23.33 m
B3
Rc = 17.63 m
Rc = 2.91 m
B7
B5
Rc = 4.66 m
B6
Rc = 13.67 m
B8
Rc = 16.86 m
0
10
20
40 Meters
N

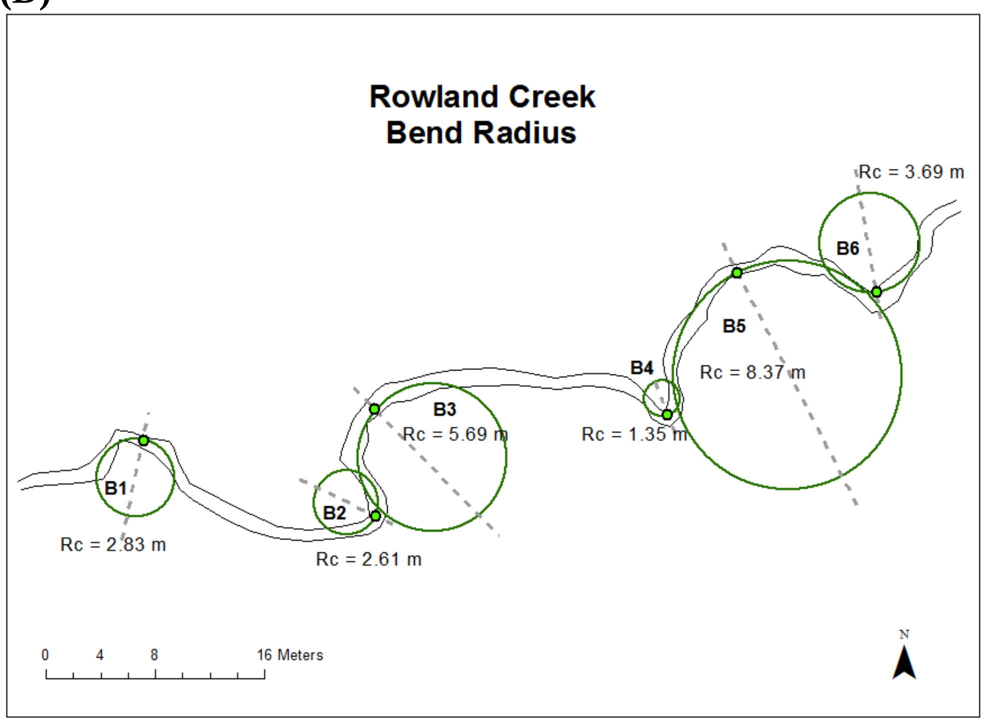
(B)


Carman Creek - Upper (Three Corner Meadow)
Bend Radius
Rc = 1.32 m
B1
Rc = 1.93 m
B3
B2
Rc = 4.13 m
Rc = 0.73 m
B5
B6
B4
Rc = 0.93 m
Rc = 1.61 m
0
2
4
8 Meters
N

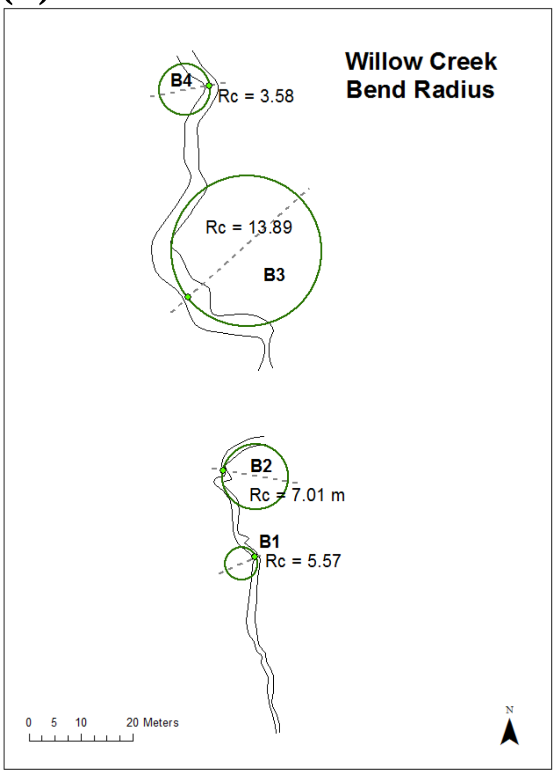
(C)


Carman Creek - Upper (Three Corner Meadow)
Bend Radius
B1
Rc = 6.67 m
Rc = 1.49 m
B2
B3
Rc = 1.14 m
Rc = 2.31 m
B5
Rc = 1.73 m
B7
B4
B6
Rc = 0.93 m
Rc = 2.55 m
0 3.5 7 14 Meters
N

(D)


Rowland Creek
Bend Radius
Rc = 3.69 m
B6
B5
Rc = 8.37 m
B4
Rc = 1.35 m
B3
Rc = 5.69 m
B2
Rc = 2.61 m
B1
Rc = 2.83 m
0 4 8 16 Meters
N

(E)



(F)

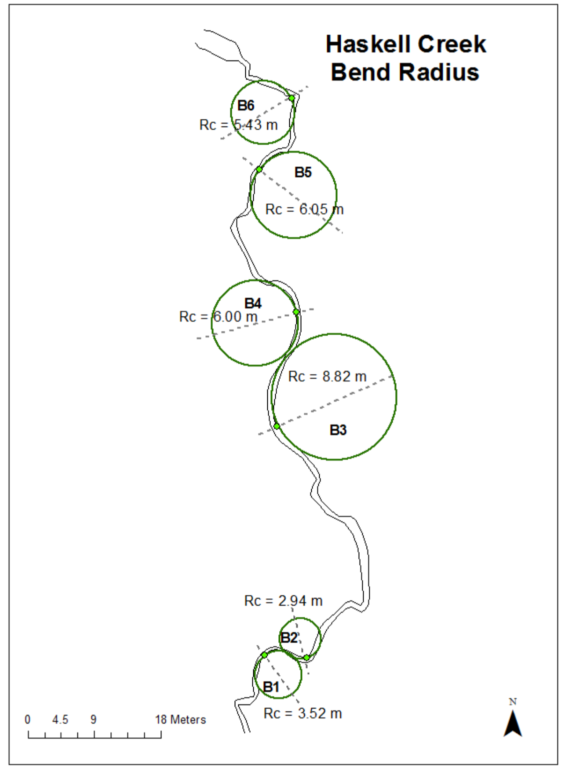


Figure 7. Radius of curvature (r_c) for meadow stream bends.

Five out of seven reaches had r_m/w values larger than 3, although the spread of bend radii measurements within each reach was highly variable as evidenced by the standard deviations (Table 5). Only 12% of all bends had r_m/w values between 2 and 3; 28% had values less than 2; and 60% had values greater than 3, suggesting that the meadow stream bends are much larger than in non-meadow environments. The average meadow stream r_m/w (5.54) is almost double the highest value considered normal by Leopold and Wolman (1960). Due to the small meadow stream sample size (n = 7) a t-test comparing the average r_m/w values of the sample streams to the Leopold and

Wolman (1960) results did not show a statistically significant difference at the 95% confidence level.

Table 5 Summary of radius of curvature to channel width results as compared to Leopold and Wolman (1960)

Reach name	*Total # bends*	*r_m/w*	*Standard deviation (s)*
Carman Creek North – Knuthson Meadow	6	7.04	2.97
Carman Creek South – Knuthson Meadow	8	7.31	5.49
Carman Creek Upper – Three Corner Meadow	6	1.07	0.75
Carman Creek Lower – Three Corner Meadow	7	1.72	1.97
Willow Creek	4	5.33	3.18
Haskell Creek	6	11.38	4.37
Rowland Creek	6	4.93	3.06
	AVERAGE	5.54	4.66

Statistical significance (t-test) for radius of curvature

Leopold and Wolman (1960)	Meadow Streams
$r_m/w = 3.1$	$r_m/w = 5.54$
$n = 50$	$s = 4.66$
	$n = 7$

$\alpha = 0.05$
$t = 1.385$
$0.250 > P > 0.200$
Accept H_o – no significant difference

Abundant vegetation can stabilize lateral channel movement and prevent bank erosion, leading to wide bends (Micheli and Kirchner, 2002). The exception to this finding is Carman Creek Upper in Three Corner Meadow which had a smaller r_m/w value

(1.77) than the Leopold and Wolman (1960) standard. This reach is located under heavy tree cover while the other reaches are located in relatively open meadow terrain. Tree roots in Three Corner Meadow regularly intersect the stream channel and may cause enough bank erosion to create smaller bends. The restored reaches (Carman Creek and Haskell Creek) had the largest r_m/w values, which may be indicative of a pre-equilibrium state where the channels are still adjusting to the restoration activities. As environmental conditions such as sediment flux and water flow stabilize over time, a distinctive meander pattern may develop.

3.1.2 Meander Wavelength

Leopold and Wolman (1960) determined that average meander wavelength to width ratio (l/w) ranges from 7-10 times channel width. None of the meadow streams had an average meander wavelength to width ratio within this range (Table 6). The spread of wavelength to width ratios within each stream reach varied widely, with an average standard deviation of 15.62. Of the meander wavelengths measured, 32% had a l/w ratio less than 7; 68% were larger than 10. Due to the small sample size ($n = 7$), a t-test comparing the average l/w values of the sample streams to the Leopold and Wolman (1960) results did not show a statistically significant difference at the 95% confidence level.

Table 6 Summary of meander wavelength to channel width results as compared to Leopold and Wolman (1960)

Reach name	*Total # meander wavelengths*	*Average l/w*	*Standard deviation (s)*
Carman Creek North – Knuthson Meadow	3	27.55	9.69
Carman Creek South – Knuthson Meadow	3	15.42	16.45
Carman Creek Upper – Three Corner Meadow	2	3.52	2.63
Carman Creek Lower – Three Corner Meadow	3	1.00	0.07
Willow Creek	2	29.08	14.48
Haskell Creek	3	42.31	15.27
Rowland Creek	3	30.24	1.88
ALL REACHES	19	22.43	16.80

Statistical significance (t-test) for meander wavelength

Leopold and Wolman (1960)	Meadow Streams
average l/w = 8.5	average l/w = 22.43
n = 50	s = 16.80
	n = 7

$\alpha = 0.05$
$t = 2.194$
$0.100 > P > 0.05$
Accept H_o – no significant difference

This, together with the radius of curvature results, suggests that bends in the meadow stream reaches tend to be much larger than average alluvial streams. These wide bends may be due to vegetation stabilizing channel banks in addition to low gradients where stream power lacks the energy for lateral erosion.

3.1.3 Straight Reach Length

While it is normal for meandering streams to contain some straight reaches, those longer than 10 channel widths (Leopold and Wolman, 1957) are considered rare. The longest straight section in each reach was divided by average channel width to assess the relationship to larger alluvial channels. Carman Creek Lower and Willow Creek were the only reaches with a straight length to width ratio lower than 10. The ratios for the five remaining reaches exceeded 10, with the Knuthson Meadow reaches containing the highest values. When taken together, the average length to width ratio for all straight reaches was 21.30 (s = 10.82), far exceeding the Leopold and Wolman (1957) results.

Knuthson Meadow contained the longest straight sections, located directly downstream of a beaver dam. This area was vegetated with significant amounts of grass and sedge and did not contain larger, woody vegetation such as willows. The absence of significant channel perturbations, such as large substrate or roots, may contribute to these long straight reaches in Knuthson Meadow. These features may also be indicative of a pre-equilibrium state with the channel still adjusting to the Carman Valley restoration project. Three Corner Meadow, Willow Creek, and Rowland Creek exhibited the smallest straight reach to channel width ratios. These channels are all located near stands of trees and woody debris which may influence bend development due to roots intersecting the channel and the necessity of the channel to flow around tree trunks.

Combined with the radius of curvature and meander wavelength results, it seems probable that environmental variables, such as low gradient, small channel width, and lack of variability of sediment input influence the formation of channels with relatively large bends and long straight reaches. Since the natural tendency of a river is to form meanders as an additional form of energy dissipation (Yang, 1971), straight reaches may be considered "temporary" features (Langbein and Leopold, 1966). This would support the idea of a pre-equilibrium state, suggesting that the meadow channels are continuing to adjust to changing environmental variables such as flow regime, sediment input, and vegetation distribution. Continued research is needed to determine if the straight reaches in the study streams are in a state of flux, or if they are an inherent, stable characteristic of the low-energy, low-gradient meadow environment.

3.2 Bedform Characteristics

Bedform characteristics, such as pools and riffles, form the characteristic undulation of the channel bed and provide stable spawning and rearing habitat for fish and other aquatic organisms (Leopold and Wolman, 1957; Gregory et al., 1994; Gurnell and Sweet, 1998). Pools are topographic lows where fine sediment accumulates while riffles are topographic highs that function as storage areas for coarser bed materials (Richards, 1976; Keller and Melhorn, 1978; Beschta and Platts, 1986). These regular, undulating sequences form as a means of self-adjustment to minimize energy loss within a stream system (Yang, 1971).

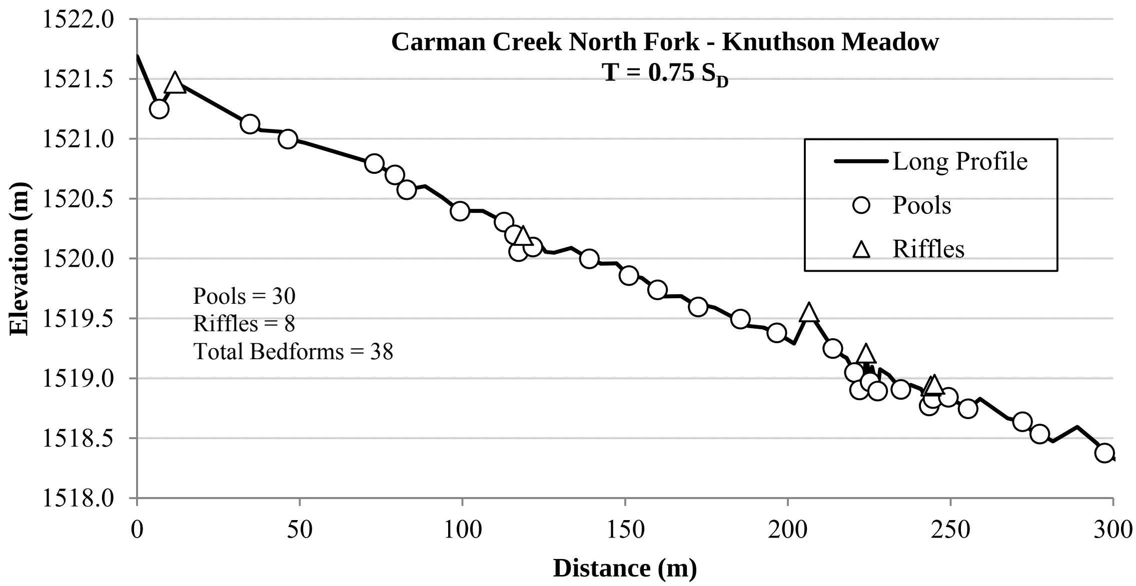
Typical pool-riffle sequences have not fully developed in the study stream reaches, therefore the term “pool-riffle sequence” is loosely applied. In most reaches, numerous scour pools have developed as a result of in-stream obstructions such as roots or large substrate. These pools tend to be connected by stretches of resistant grass sod that approximate the function of riffles by providing an energy-drop mechanism. These bedforms may indicate an early stage in the continuum of channel development, pointing to a pre-equilibrium state. The bedforms may also be related to discontinuous gullies, a series of discrete scour holes separated by bare ground or vegetation (Leopold and Miller, 1956). Bedform spacing and pool-forming mechanisms were characterized to demonstrate how the meadow channels compare to larger alluvial streams and to examine how these channels may fit into the discontinuous stream framework.

3.2.1 Bedform Spacing

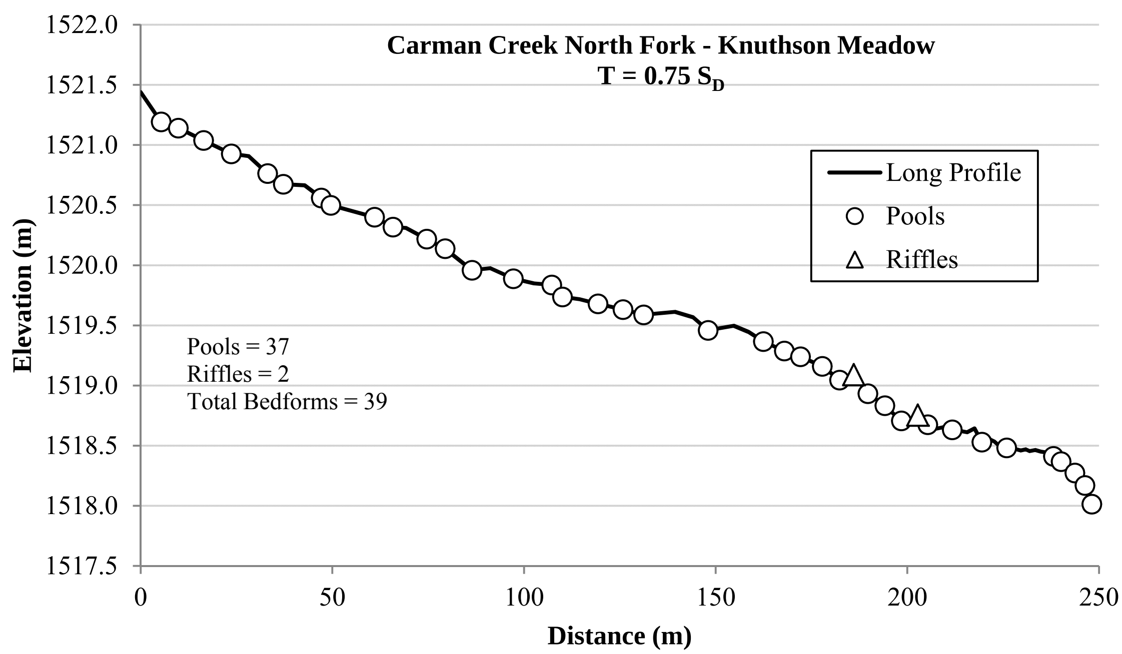
Leopold et al. (1964) calculated that pools and riffles are regularly spaced at 5-7 channel widths. Subsequent research on pool-riffle spacing (PRS) supports the spacing of 5-7 channel widths (Keller, 1972; Keller and Melhorn, 1978). The addition of roughness elements, such as large woody debris or large substrate, in the channel bed or banks can also increase the variability of pool-riffle size and spacing (Beschta and Platts, 1986).

The bedform differencing technique (O’Neill and Abrahams, 1984) was used to objectively identify the total number of bedforms (pools and riffles) in each longitudinal profile (Figure 8).

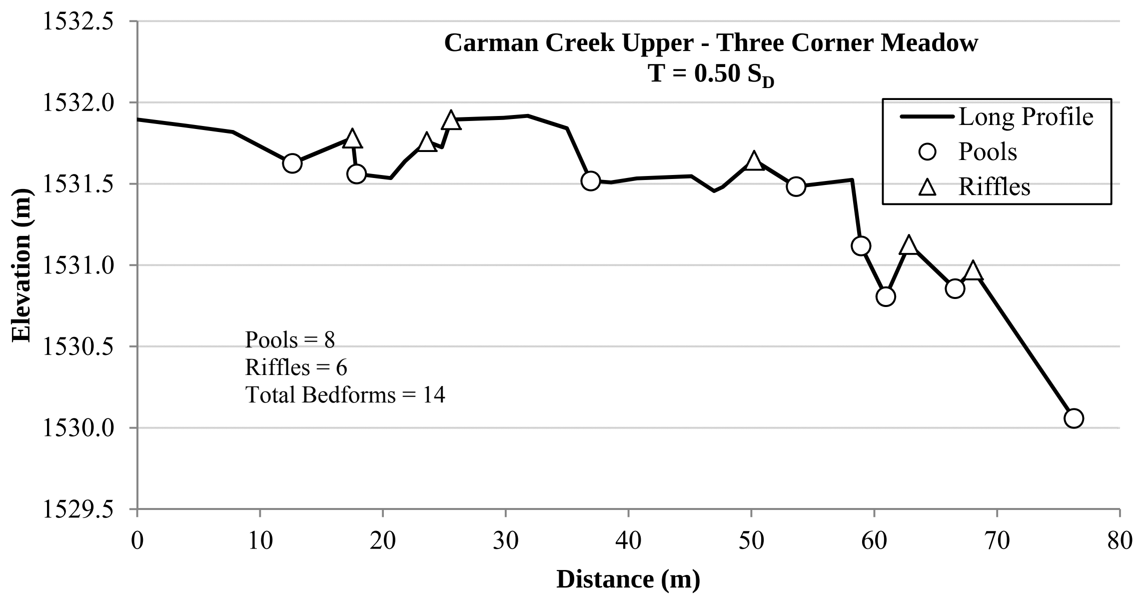
(A)


Carman Creek North Fork - Knuthson Meadow
T = 0.75 S_D
Long Profile
Pools
Riffles
Pools = 30
Riffles = 8
Total Bedforms = 38
Elevation (m)
1522.0
1521.5
1521.0
1520.5
1520.0
1519.5
1519.0
1518.5
1518.0
Distance (m)
0
50
100
150
200
250
300

(B)

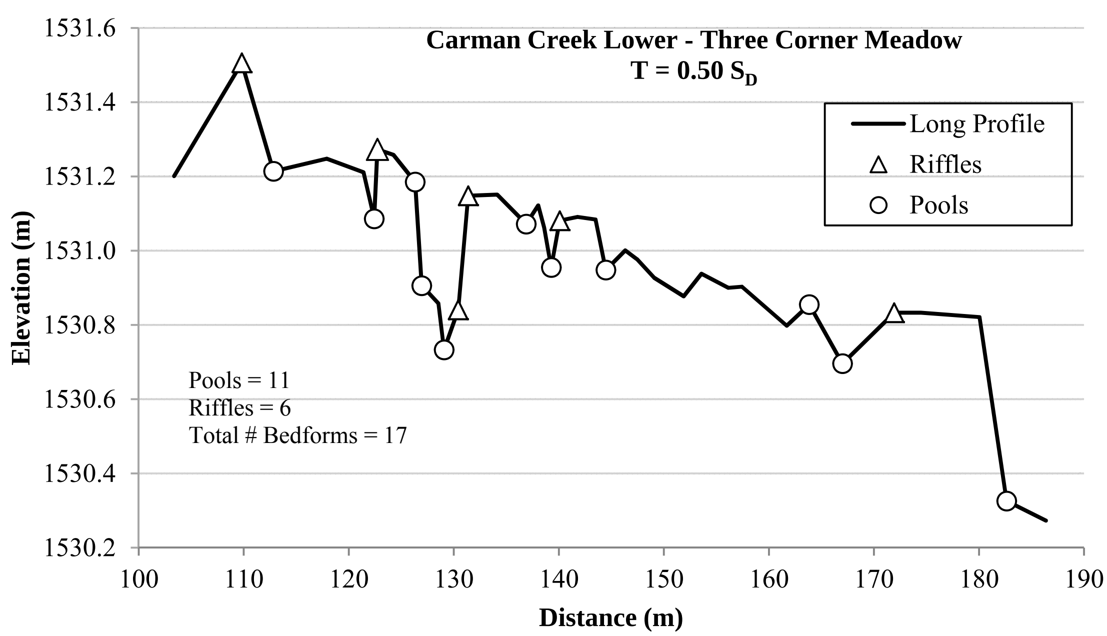

Carman Creek North Fork - Knuthson Meadow
T = 0.75 S_D
Long Profile
Pools
Riffles
Pools = 37
Riffles = 2
Total Bedforms = 39
Elevation (m)
1522.0
1521.5
1521.0
1520.5
1520.0
1519.5
1519.0
1518.5
1518.0
1517.5
Distance (m)
0
50
100
150
200
250

(C)



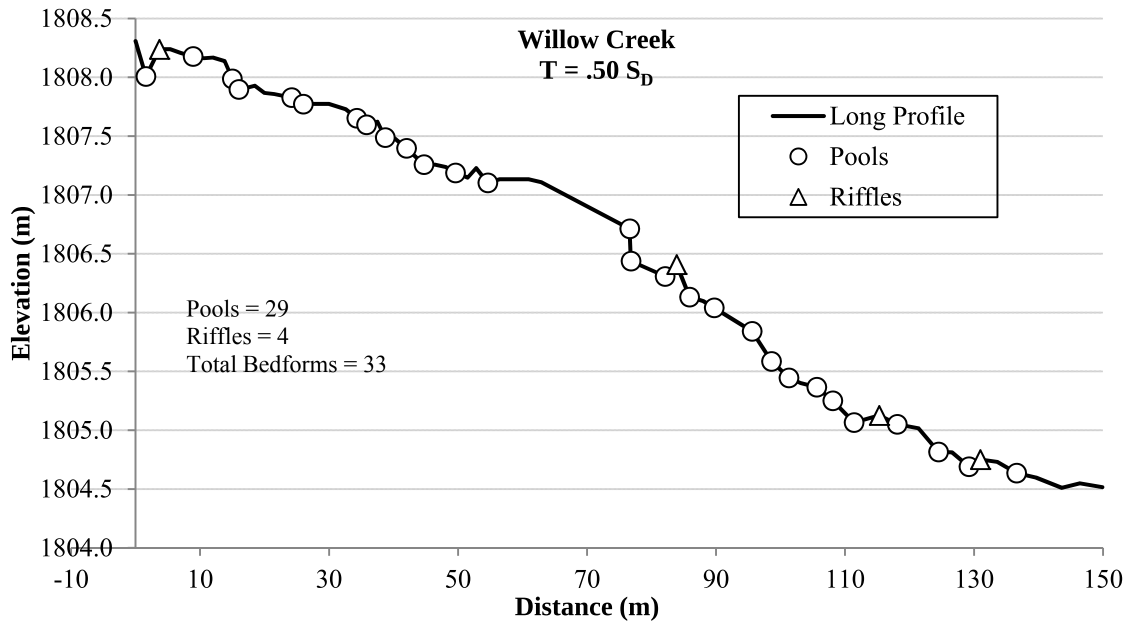
Carman Creek Upper - Three Corner Meadow
T = 0.50 S_D
Long Profile
Pools
Riffles
Pools = 8
Riffles = 6
Total Bedforms = 14
Elevation (m)
Distance (m)
1532.5
1532.0
1531.5
1531.0
1530.5
1530.0
1529.5
0
10
20
30
40
50
60
70
80

(D)

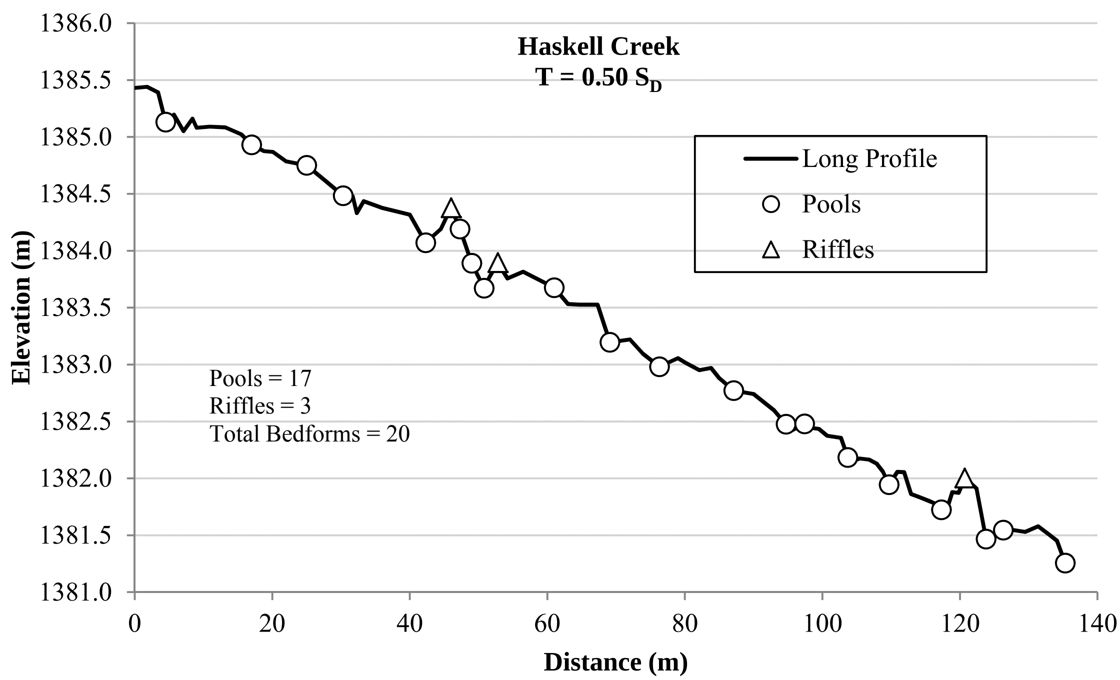


Carman Creek Lower - Three Corner Meadow
T = 0.50 S_D
Long Profile
Riffles
Pools
Pools = 11
Riffles = 6
Total # Bedforms = 17
Elevation (m)
Distance (m)
1531.6
1531.4
1531.2
1531.0
1530.8
1530.6
1530.4
1530.2
100
110
120
130
140
150
160
170
180
190

(E)


Willow Creek
T = .50 S_D
Long Profile
Pools
Riffles
Pools = 29
Riffles = 4
Total Bedforms = 33
Elevation (m)
Distance (m)
1808.5
1808.0
1807.5
1807.0
1806.5
1806.0
1805.5
1805.0
1804.5
1804.0
-10
10
30
50
70
90
110
130
150

(F)


Haskell Creek
T = 0.50 S_D
Long Profile
Pools
Riffles
Pools = 17
Riffles = 3
Total Bedforms = 20
Elevation (m)
Distance (m)
1386.0
1385.5
1385.0
1384.5
1384.0
1383.5
1383.0
1382.5
1382.0
1381.5
1381.0
0
20
40
60
80
100
120
140

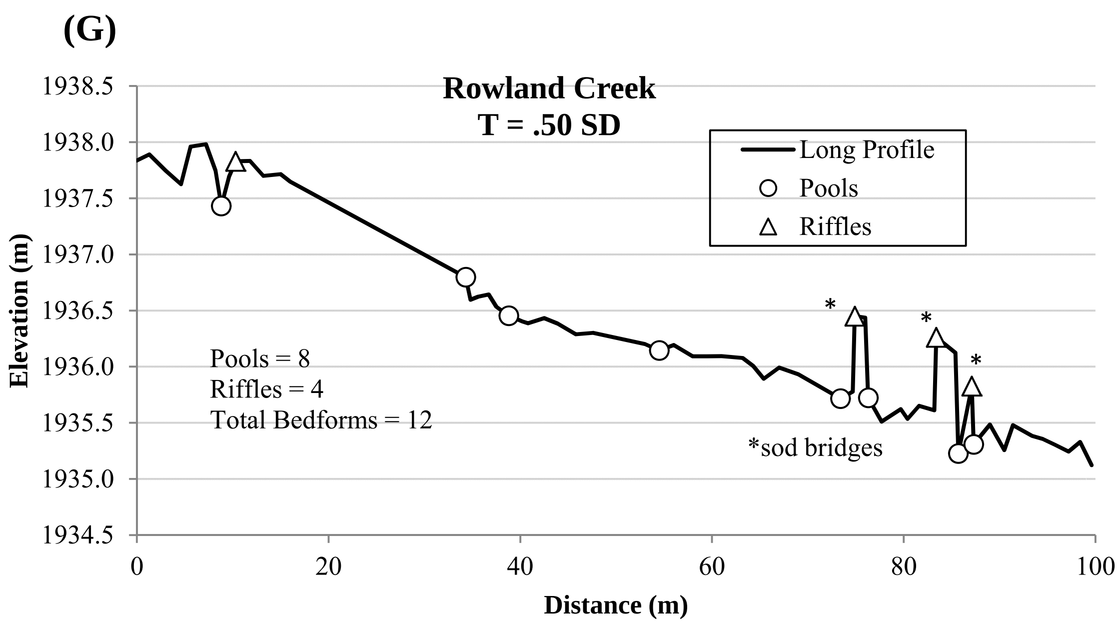


Figure 8. Longitudinal profiles showing locations of pools (circles) and riffles (triangles) identified by the bedform differencing technique.

A PRS is defined as any consecutive pool and riffle, or vice versa. Rather than identifying roughly equal numbers of pools and riffles as in a typical alluvial stream system, the technique identified four times as many pools than riffles, with an average of 20 pools versus 5 riffles per reach (Figure 9).

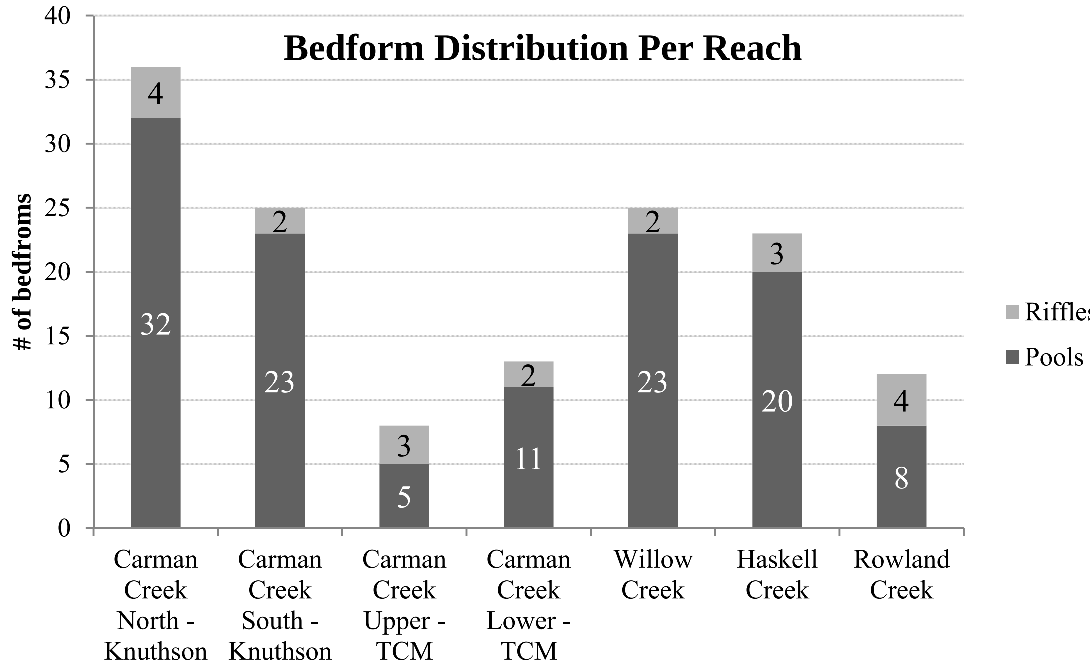


Figure 9. Bedform distribution for each stream reach. The ratio of pools to riffles is 4 to 1.

The abundance of pools in each reach suggests that the typical undulating longitudinal profile is not common in these meadow channels. In contrast, a linear downward profile containing slight elevation differences dominates. Despite the apparent differences, the presence of grass sod serves a similar energy-drop function between pools as in typical alluvial stream systems.

Average bedform-spacing to channel-width ratio was measured by dividing the total study reach length by the number of bedforms and dividing the result by average channel width. The same method was applied to the number of pool-riffle sequences per reach for comparison (Table 7).

Table 7 Bedform and pool-riffle sequences to channel width ratios

Stream reach	*T-value (S_D)*	*Total # bedforms*	*Bedform/ width*	*Total # PRS*	*PRS/ width*
Carman Creek North Fork – Knuthson Meadow	0.75	38	6.62	6	41.94
Carman Creek South Fork – Knuthson Meadow	0.75	39	4.33	2	84.39
Carman Creek Upper - Three Corner Meadow	0.75	14	3.30	6	7.7
Carman Creek Lower - Three Corner Meadow	0.75	17	7.83	6	22.19
Willow Creek	0.50	33	3.22	4	26.56
Haskell Creek	0.50	24	11.72	3	93.77
Rowland Creek	0.50	12	10.01	4	30.04
TOTAL		***173***	**-**	***31***	**-**
AVERAGE		***25***	***6.72***	***4***	***43.80***

Statistical significance (t-test) for Bedform/Width

Keller and Melhorn (1978)	Meadow Streams
average spacing = 5.98	average spacing = 6.72
n = 11	s = 3.09
	n = 7

$\alpha = 0.05$
t = 0.634
Accept H_o – no significant difference

Statistical significance (t-test) for PRS/Width

Keller and Melhorn (1978)	Meadow Streams
average spacing = 5.98	average spacing = 43.80
n = 11	s = 30.25
	n = 7

$\alpha = 0.05$
t = 3.308
Reject H_o – significant difference

A t-test comparing average bedform/width to the pool-to-pool spacing results of Keller and Melhorn (1978) showed no significant different at the 95% confidence level, suggesting that the bedform morphology is similar to typical pool-riffle systems. Average bedform to width spacing (6.72) was within the 5-7 spacing with a relatively small standard deviation (3.09). In contrast, a significant difference at the 95% confidence level was found for PRS/width as compared to Keller and Melhorn (1978). PRS/width values have a much higher standard deviation (30.25), with the average PRS/width ratio (43.80) far exceeding 5-7 channel widths. This variability indicates that pool-riffle sequences do not constitute a reliable form of measurement for these channels and that bedform-to-bedform spacing is a more appropriate measuring stick (Figure 10).

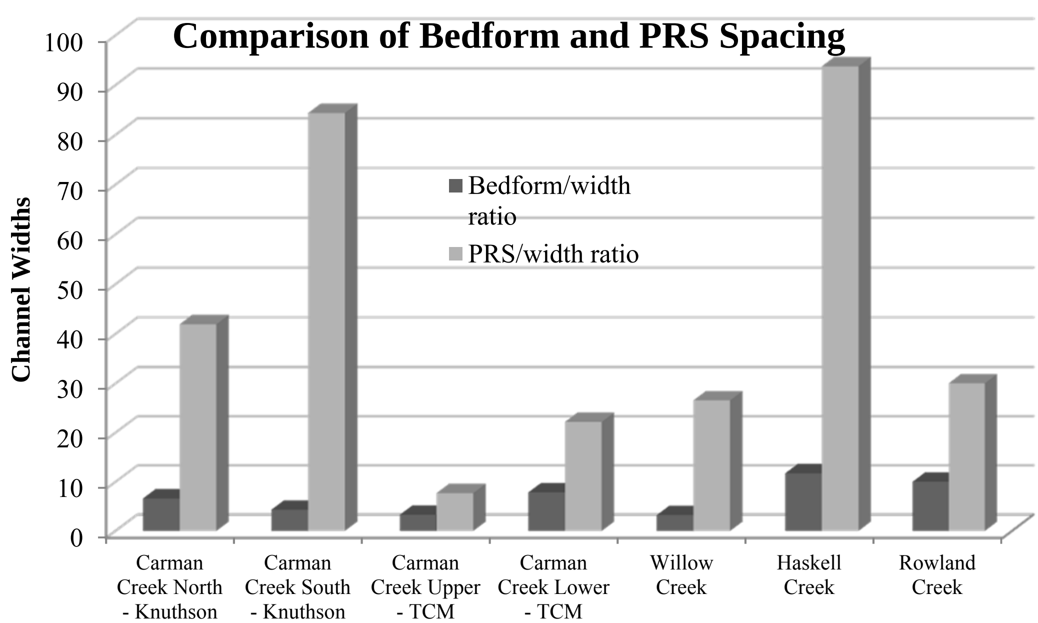


Figure 10. Comparison of bedform and PRS to channel width ratio for each reach. PRS/width ratios far exceed bedform/width ratios due to the limited number of pool-riffle sequences in the meadow streams. Bedform/width spacing is much more consistent across reaches.

The results show that bedforms spaced within 5-7 channel widths are a consistent, cyclic phenomenon of these meadow channels, similar to the pool-riffle cycle found in larger alluvial channels.

The longitudinal profiles of the study stream reaches may be related to discontinuous channels, which are formed by cyclic phases of aggradation and degradation on the valley floor. The discontinuous nature arises in places where the channel slope is less than the original valley floor (Leopold and Miller, 1956). A defining characteristic of a discontinuous gully is the low bed gradient, typically between 1-3° (Eyles, 1977), associated with a narrow channel width (Leopold and Miller, 1956). Plunge pools deepen a discontinuous gully by undercutting during a storm flow, a feature that is evident in the meadow channels (Figure 11). Hagberg (1995) found that headcut migration due to plunge pools are the dominant erosional process in Sierra meadow streams.

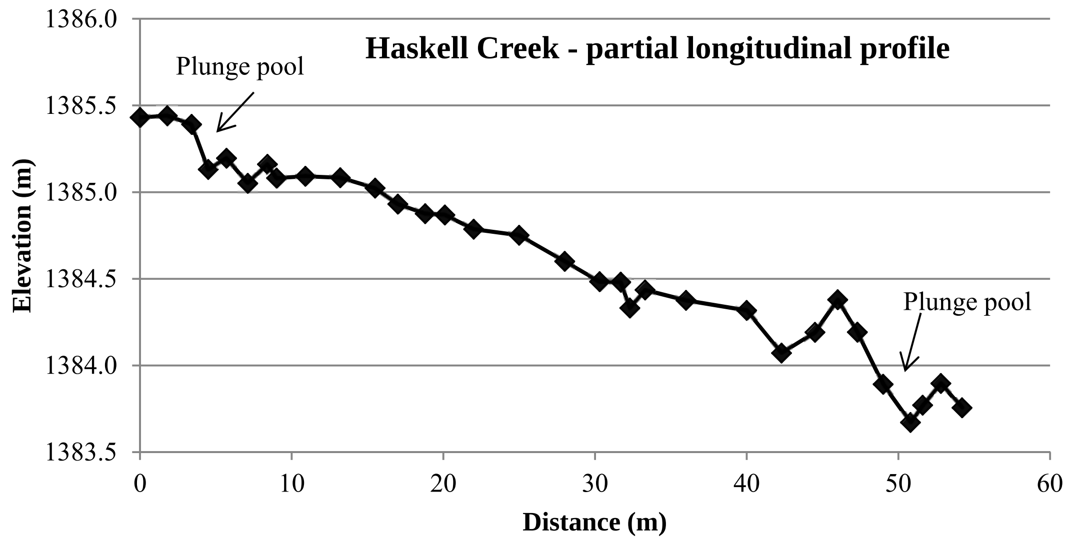


Figure 11. Partial longitudinal profile of Haskell Creek showing the location of plunge pool headcuts that are deepening the channel.

The nature of the bedforms, especially the grass riffles, may also approximate descriptions of vegetated sediment bars that form between ponds in place of the typical pool-riffle. This phenomenon has been observed in analogous Australian landscapes, termed a "swampy meadow" by Mactaggart et al. (2008). The bedform features, combined with the narrow, low-gradient nature of the meadow channels indicate similarities to discontinuous gullies and channels.

3.2.2 Pool-Forming Mechanisms

Each reach was analyzed to evaluate the mechanisms causing a significant number of pools to form. Pools are more likely to develop where streamside obstructions cause eddies to scour deep holes in the channel bed (Lisle, 1986; Wohl et al., 1993).

Low-gradient reaches have also been shown to be more susceptible to channel bed scour as channel erodibility relative to flow strength increases (Wohl et al,. 1993). Each pool was categorized based on pool-forming mechanisms observed in the field (Figure 12).

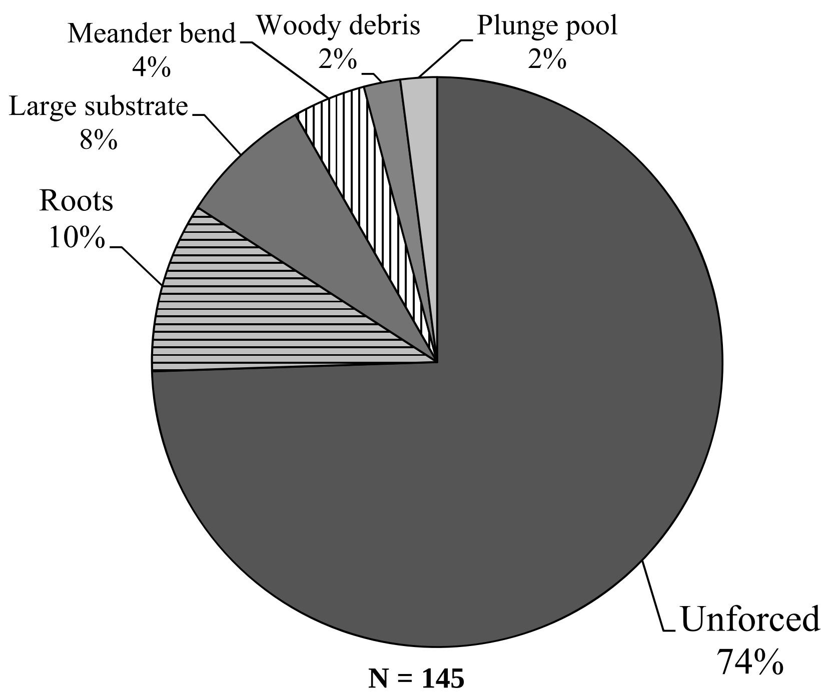


Figure 12. Mechanisms causing the formation of pools in the study reaches. Unforced pools are most common, followed by forced pools of various causes.

The majority of pools (74%) were “unforced”, meaning there was no obvious mechanism for formation except positive feedback resulting from the potential combination of water flow, sediment input, and rain-on-snow events. “Forced” pools (26%) were those with a clear, visible mechanism for formation, such as scour caused by tree roots, large substrate, location at a meander bend apex, woody debris, and plunge pools.

Each location contained different environmental factors contributing to pool formation. In Carman Creek (Three Corner Meadow), deep pools occurred where roots and large substrate caused eddies to scour the channel (Figure 13).

Figure 13. A scour pool caused by extensive tree roots in Carman Creek, Three Corner Meadow.

In Willow Creek, large cobbles and boulders forced 28% of pools. In Haskell Creek, 15% of pools were located at meander bend apices and 15% were formed from plunge pools at terraced elevation drops. In Rowland Creek, 36% of pools were formed by roots or at meander bends, while large substrate accounted for 9% of pools. The two most sinuous reaches, Haskell Creek and Rowland Creek, contained the largest number of pools at meander bend apices.

Headcut development in the resistant sod contributed to pool formation at regular, cyclic intervals. For example, several headcut steps were observed in Haskell Creek, leading to the creation of plunge pools (Figure 14).

Figure 14. Headcut step in sod creating a plunge pool in Haskell Creek. Gray arrow indicates flow direction.

In Rowland Creek, resistant sod bridges (a form of piping) developed from eroding headcuts, allowing water to penetrate deeply into the bed material (Figure 15). Piping has been linked to discontinuous gully formation where it is a mechanism for deepening the channel (Leopold and Miller, 1956).

Figure 15. Surveying a sod bridge in the channel of Rowland Creek. The top of the bridge is indicated by the white arrow. Flow direction is indicated by the gray arrow.

The combination of shallow gradients, resistant sod, and streamside obstructions (substrate and woody debris) caused extensive pool formation in these meadow channels. The environmental factors leading to pool creation have important implications for physical habitat which should be considered when planning meadow restorations (Montgomery et al. 1995; Gurnell and Sweet 1998).

3.2.3 Errors and Uncertainties

The lack of visibility of the narrow stream channels due to vegetation (most notably in Knuthson Meadow) impaired the surveying process. In particular, identification of bankfull width was problematic due to the lack of clear banks resulting from the discontinuous nature of the reaches. In many of the reaches, bankfull width was most likely underestimated due to the inability to judge channel boundaries and the absence of visual clues. Where possible, environmental signals such as vegetation change or topographic breaks indicated bankfull width, but these clues were not always present. It is difficult to judge the magnitude of these potential measurement errors as they were not systematic and varied according to location. Bankfull distances may have been underestimated by as much as 0.5 m due to inconclusive visual clues. Field notes at these survey points were labeled "indistinct" and the data excluded from the final analysis, which may have resulted in an overall underestimation of average channel widths.

The selection of stream morphometric elements, such as bends and straight reaches, was a subjective process due to the highly variable and indistinct nature of planform characteristics in the meadow environment. The identification of bends during the analysis process was challenging, as these features were not as fully developed as typical alluvial streams. While individual bend radii and meander wavelength measurements may vary according to subjective opinion, any average measurements should still support the finding of wider stream bends and longer straight lengths.

The bedform differencing technique was much more sensitive to pools than riffles. As shown in the analysis, the primary bedform features in the meadow streams consisted of a series of scour pools that formed along a shallow gradient composed of grass sod.

The strength of the bedform differencing technique is its ability to objectively identify pools and riffles by establishing a tolerance value (T) derived from the standard deviation (S_D) of elevation differences in the longitudinal profile (O'Neill and Abrahams, 1984). The low gradient of the grass sod made it difficult to use the technique to identify positive values sufficient to exceed the tolerance. It is possible that surveying points at a finer resolution may address this problem, but the dominant erosional processes inherent at this stage of development in the meadow streams seem to favor the creation of pools over riffles.

4. Conclusion:

This research characterized morphological features of seven small, discontinuous montane meadow stream reaches in the northern Sierra Nevada and compared these features to models of larger alluvial streams found in the literature. The meadow channels mirror typical alluvial streams in several ways – for example, bedform features tend to occur at regular, cyclic intervals of 5-7 channel widths. Pool-forcing mechanisms, such as large substrate, large woody debris, and resistant sod, are also similar to those found in regular alluvial channels. Despite these similarities, the meadow channels contained riffles composed of grass sod instead of coarse sediment. These grass riffles connected a series of pools along the channel bed, providing the same energy-drop function as riffles or steps. This morphology indicates that bedform characteristics may be more similar to that of discontinuous channels and typical pool-riffle sequences may not be an appropriate means of measurement.

Planform features did not conform to standard models – for example, the meadow streams contained larger bend radii, meander wavelengths, and longer straight reaches. This type of channel morphology may be indicative of insufficient time for dynamic equilibrium involving not only erosional but also well-developed depositional bedforms. Other factors contributing to non-standard planform morphology are extensive hydric and mesic vegetation that limit channel movement, prevent significant bank erosion and the formation of tight meanders.

These results suggest that some planform aspects of the meadow channels can be considered distinct in their morphology from larger alluvial channels. However, bedform features were found to follow similar cyclic patterns to larger channels based on quantitative models found in the literature. Although this study is focused on a relatively small sample size of montane meadows in the northern Sierra Nevada and should not be considered representative of all wetland streams, the comparison of morphological features provides a rudimentary framework for similar meadow channels.

Land managers can apply this knowledge to develop custom restoration and monitoring plans. By considering distinct planform and bedform features, better channel designs appropriate for the low-gradient, heavily vegetated meadow environment can be developed. With growing recognition of the extraordinary values provided by meadow habitats in the Sierra Nevada, restoration projects have become increasingly common (Purdy and Moyle, 2006). As a result, land managers must have the necessary tools at their disposal to properly evaluate and monitor post-restoration meadow conditions. The physical integrity of a stream provides the foundation for biotic and hydrologic systems, and restorations cannot be considered successful without evaluating a stream's unique physical structure (Graf, 2001). This research hopefully contributes to a better understanding of the mechanisms underlying small, discontinuous channel development and to the broader literature on wetland stream morphology and restoration.

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