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Morphology of small, discontinuous montane meadow streams in the Sierra Nevada

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ABSTRACT

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, especially as we move to larger watersheds and higher precipitation and runoff, but planform features are less developed and highly influenced by vegetation. Restoration efforts can benefit from considering how planform and bedform channel patterns develop in these meadows.

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1. Introduction

Montane meadows in the Sierra Nevada of California are unique riparian wetland ecosystems where seasonal fluctuations in water saturation provide rich environments for biota at elevations between 600 and 3500 m (Rundel et al., 1977). 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 < 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, and especially wet meadows, habitats for indicator species such as Sierra yellow-legged frog (*Rana sierra*; Viers et al., 2013) and subspecies of the Southwestern willow flycatcher (*Empidonax traillii*; Finch and Stoleson, 2000). 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 this mountain range, 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 on habitat quality, and the effects extend not only across the riparian corridor but also longitudinally. 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 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, and a greater channel width at riffles (Jurmu and Andrle, 1997). Pool–riffle locations were more inconsistent because of the low-energy gradient in wetland environments (Jurmu, 2002). Watters and Stanley (2007) found that peatland channels had lower

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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).

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 length of 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 in northern California is composed of steep valleys interspersed with shallow alluvial basins extinct lakes. Today, many Sierra alluvial valleys include meadows, whether developed from lake succession or groundwater, constituting the most biologically active plant communities in the mountain range (Ratliff, 1982). This region typically receives the majority of its precipitation during the winter months, with annual rainfall averages varying from 500 to 2000 mm (PRISM, 2004), depending on topography and its effects on uplift and rainshadow. 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 in the Mediterranean climate. During the snowmelt season in the meadows studied, overland flow dominates the entire meadow surface while subsurface drainage takes over during the dry summer months. Meadow sod tends to be erosion-resistant owing to the dominance of hydric and mesic herbaceous vegetation with dense root masses. Xeric vegetation communities, including sagebrush (*Artemisia tridentata*), are present in areas where the groundwater table is low.

Many 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 American 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 (Fig. 1).

Meadows in the Sierra Nevada have been 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 because of 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).

The Carman Creek system provides an example of a wet meadow that underwent restoration to restore hydrologic function and biotic habitat. As early as the 1950s, the area was designated as a severely impaired ecosystem largely because of railroad logging and livestock grazing that began in the mid-1800s (SVRCD, 2004). Carman Creek became incised into a gully running parallel to the railroad tracks, and the meadow subsequently dried out, with vegetation succession from wet meadow species, such as sedges and rushes, to dry meadow species such as sagebrush (SVRCD, 2004). The gully cut off hydrologic connectivity to the floodplain causing significant lowering of the water table and loss of water storage capability (SVRCD, 2004). Restoration efforts in the early 2000s helped reestablish floodplain connectivity and wildlife habitat. As the environmental benefits of meadows are increasingly recognized, similar restoration projects are becoming more common in this region (Purdy and Moyle, 2006).

Fig. 1. Instead of riffles composed of coarse sediment, the meadow channels exhibit '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.

1.2. Study site descriptions

Stream reaches in the Feather River basin were selected on the basis of the presence of grass sod energy drops acting similarly to riffles. Four stream reaches were selected along Carman Creek, with two reaches in Three Corner Meadow and two reaches in Knuthson Meadow, and one reach each was identified along Willow Creek, Haskell Creek, and Rowland Creek (Fig. 2).

Five of seven reaches were located in meadows restored using 'pond-and-plug' methods, which redirect surface flows from the paths of the incised channel, where the ponds and plugs are built, onto adjacent meadow surfaces where in some cases preexisting smaller channels are reoccupied (Lindquist and Wilcox, 2000). Study sites were selected to document a range of conditions under which the grass sod riffle energy-drop phenomenon occurs. All sites (Table 1) were chosen based on recommendations from restoration geomorphologists with the Feather River Coordinated Resource Management Group (Plumas Corporation, Quincy, CA) and Tahoe National Forest (U.S. Forest Service). Site selection was further refined based on the following criteria:

- location in a montane meadow (600–3500 m elevation);
- small drainage area (<50 km^2); and
- 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 laser level 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

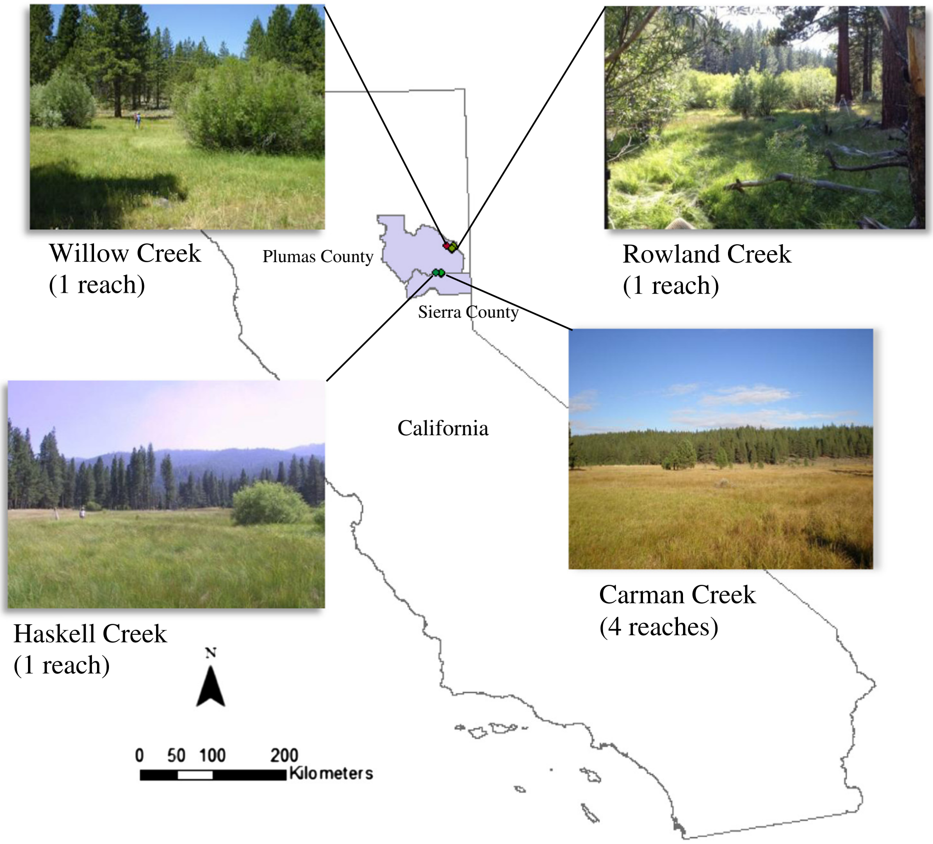

Fig. 2. Map of California showing study site locations and photos of meadow sites.

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. In order to repeat surveys in the future, benchmarks were established on permanent features such as piezometers, fence stakes, and spikes hammered into tree trunks. A Topcon laser level and rod-mounted sensor were used to capture the relative elevations of survey points. We surveyed each point along the thalweg at ~1.5-m intervals, with cross sections measured at ~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. A Trimble GeoXH GPS unit acquired *x*, *y*, *z* coordinates for each point. The GPS horizontal accuracy after differential correction varied across sites but was generally between 0 and 15 cm, with the exception of Three Corner Meadow which had the heaviest tree cover.

The same points surveyed with the laser level were also surveyed with the GPS unit. For quality assurance through redundancy, station distances between successive points were also 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 owing to lack of distinct banks and the presence of extensive vegetation (Fig. 3), especially in sections of Knuthson Meadow where relatively recent (~10 years) pond-and-plug restoration has provided little time for equilibrium channel morphologies to develop. 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 because of the absence of clearly defined terraces, presence of surface water beyond the channel, and high permeability of channel banks (Jurmu and Andrle, 1997;

Table 1
Summary of physical characteristics of study reaches.

Stream Reach	Elev. (m)	Watershed area (km^2)	Stream flow	Restoration status	Avg annual precipitation (mm)
Carman Creek north fork – Knuthson Meadow	1520	30	Seasonal	Restored	760
Carman Creek south fork – Knuthson Meadow	1520	30	Seasonal	Restored	760
Carman Creek upper – Three Corner Meadow	1530	16	Seasonal	Restored	760
Carman Creek lower – Three Corner Meadow	1530	16	Seasonal	Restored	760
Willow Creek	1808	17	Seasonal	Unrestored	650
Haskell Creek	1384	11	Perennial	Restored	1100
Rowland Creek	1937	48	Perennial	Unrestored	590

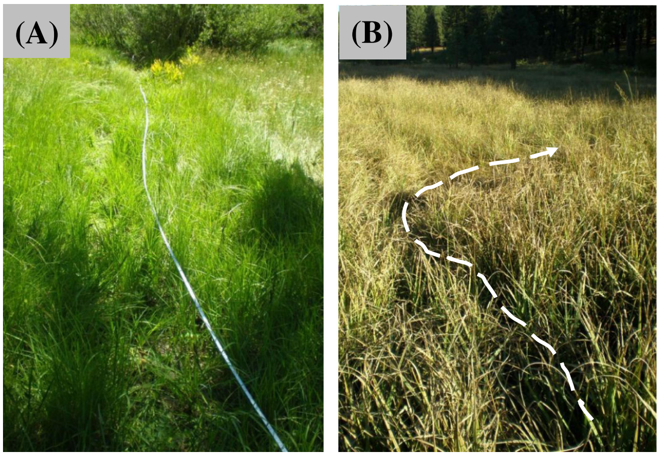

Fig. 3. Examples of small, indistinct meadow stream channels observed during the dry season. (A) The white measuring tape marks the location of the channel in Willow Creek. (B) The dashed white line indicates the location of the channel in the Knuthson Meadow reach of Carman Creek.

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 10 (ESRI, 2012) 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, which has been applied to smaller channels with less clearly developed bedforms (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 (leaving open for interpretation whether our detected 'riffles' are true riffles). 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 we found that T-values between $0.50S_D$ and $0.75S_D$ most closely approximated field observations (scouring) for bedform locations.

3. Results

Key morphological features were measured for each stream reach and summarized in Table 2. These values were then compared to the morphological features as defined in the literature and summarized in Table 3.

3.1. Planform characteristics

Previously documented relationships among channel planform morphometries include those between meander length, channel width, and radius of curvature. Planform types are distinguished by degrees of sinuosity (P), defined as the ratio of channel thalweg 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 ~3.0 (highly sinuous), depending on factors contributing to channel stability such as vegetation or substrate (Schumm, 1985; Trimble, 1997). Streams with a P-value > 1.5 are considered meandering (Leopold and Wolman, 1957). 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) for meandering streams in the USA 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, meandering alluvial streams worldwide. Radius of curvature (r_c) for each study reach bend was calculated based on the following equation: $R_c = C^2/8\ M + M/2$, where C = chord length and M = middle ordinate distance. Bend radii are depicted by circles, with Carman Creek in Knuthson Meadow

Table 2
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
Substrate distribution							
Erosional (sod, bare soil)	88%	100%	41%	22%	48%	17%	23%
Depositional (cobbles, gravel, sand)	9%	0%	41%	46%	52%	75%	92%
Cobbles	*0%*	0%	*17%*	*30%*	*10%*	*10%*	*14%*
Gravel	*2%*	0%	*17%*	*8%*	*36%*	*33%*	*41%*
Sand	*0%*	0%	*7%*	*8%*	*0%*	*0%*	*0%*

Table 3
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)

as an example in Fig. 4. Bend selection was subjective owing to the indistinct nature of the meanders and low sinuosity values.

Five out of seven reaches had average r_m/w values > 3, although the spread of bend radii measurements within each reach was highly variable with standard deviations ranging from 0.75 (Carman Creek upper) to 5.49 (Carman Creek south). Only 12% of all bends had r_m/w values between 2 and 3; 28% had values < 2; and 60% had values > 3, suggesting that the meadow stream bends are larger than in non-meadow environments. The average r_m/w (5.54) is almost double the highest value considered normal by Leopold and Wolman (1960). Because of the high standard deviation ($s = 3.52$) 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.

3.1.2. Meander wavelength

Leopold and Wolman (1960) determined that average meander wavelength-to-width ratio (l/w) ranges from 7 to 10 times channel width. Out of 19 meander wavelengths measured, the average l/w ratio was 22.43, far exceeding the Leopold and Wolman (1960) standard. No bends (0%) contained an average l/w ratio within the 7-10 range; 32% had a l/w ratio < 7, while 68% were > 10. The spread of wavelength-to-width ratios within each stream reach varied widely, with an average standard deviation of 16.80, which is too great to result in a statistically significant difference from Leopold and Wolman (1960) results.

3.1.3. Straight reach length

While 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 ($s = 10.82$), more than double the maximum parameter of 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 instead of 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 caused by roots intersecting the channel and the necessity of the channel to flow around tree trunks.

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 (while often related to meander sequences) can however also form in straight channels (Knighton, 1998). Montgomery and Buffington (1997) recognized

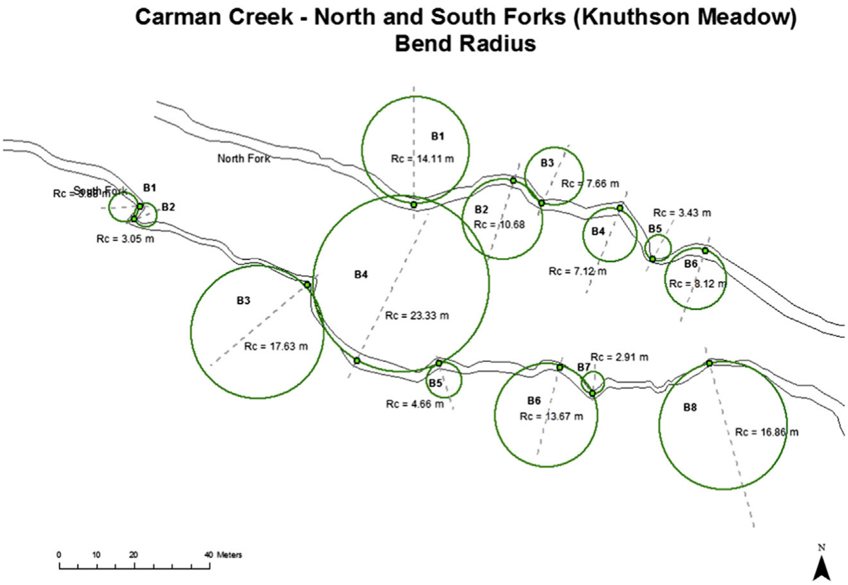

Fig. 4. An example of radius of curvature (r_c) measurements in Carman Creek – Knuthson Meadow.

pool–riffle sequences as a distinct alluvial reach morphology dependent on sediment supply and transport capacity. In our study, bedform spacing and pool-forming mechanisms were characterized to determine how the meadow channels compare to larger alluvial streams.

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 supports the model 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. The profiles for Carman Creek north (Knuthson Meadow) and Haskell Creek are shown as examples in Fig. 5 to illustrate the gradual downward slope and absence of a significant undulating pattern. A pool–riffle sequence (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, the technique identified four times as many pools than riffles, with an average of 20 pools versus 5 riffles per reach (Fig. 6). 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, other than the intermittent scour holes that stand out from the general pattern.

Because of the preponderance of pools in the study reaches, two different analyses were conducted to characterize bedform spacing patterns: (i) bedform spacing (pool *or* riffle), and (ii) pool–riffle sequence (pool *and* riffle). 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.

A *t*-test comparing average bedform/width to the pool-to-pool spacing results of Keller and Melhorn (1978) showed no significant difference at the 95% confidence level, suggesting that bedform morphology contains a similar cyclic pattern seen in typical pool–riffle systems. Average bedform-to-width spacing (6.72) was within the 5-7 widths 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). The 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 pool-to-pool bedform spacing is a more appropriate measuring stick (Fig. 7).

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

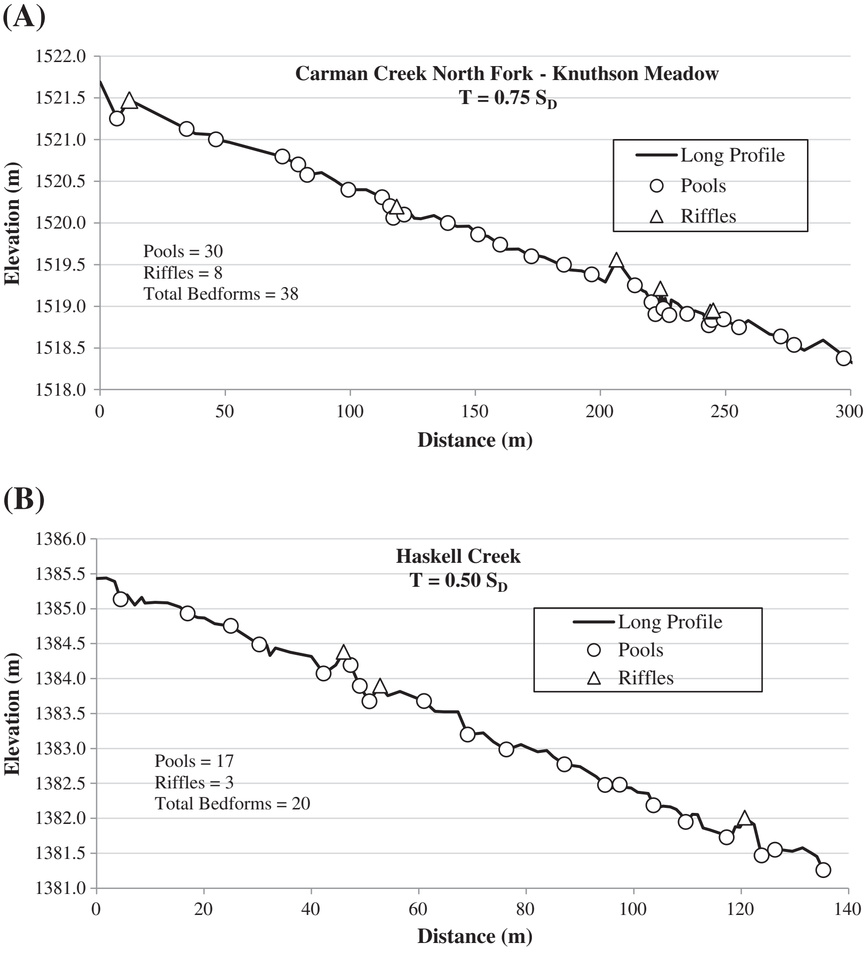

Fig. 5. Longitudinal profiles showing locations of pools (circles) and riffles (triangles) identified by the bedform differencing technique for Carman Creek north and Haskell Creek.

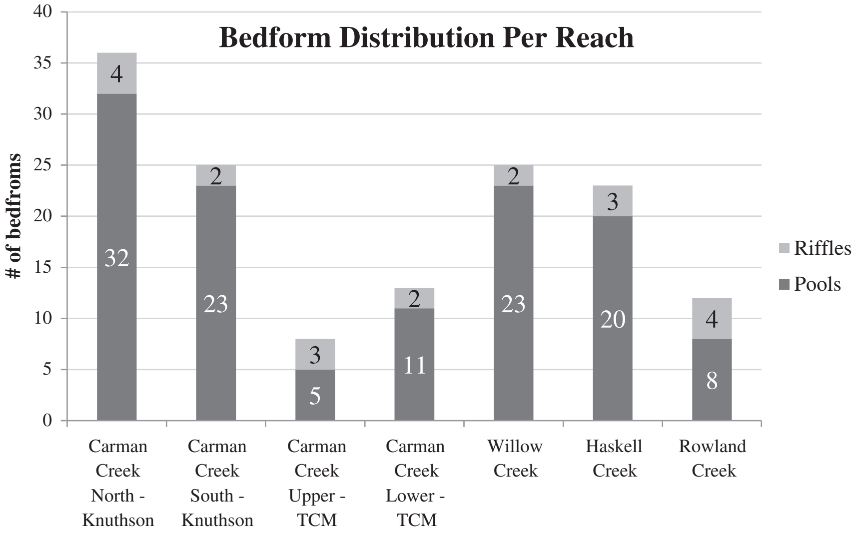

Fig. 6. Bedform distribution for each stream reach. The ratio of pools to riffles is 4 to 1.

pool was categorized based on pool-forming mechanisms observed in the field (Fig. 9).

The majority of pools (74%) were 'unforced', or had 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 adjacent to 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 (Fig. 10).

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 (Fig. 11).

In Rowland Creek, resistant sod bridges (a form of piping) developed from eroding headcuts, allowing water to penetrate deeply into the bed material (Fig. 12). Piping has been linked to discontinuous gully formation where it is a mechanism for deepening the channel (Leopold and Miller, 1956).

3.2.3. Errors and uncertainties

The lack of visibility of the narrow stream channels caused by vegetation (most notably in Knuthson Meadow) impaired the surveying process. In particular, identification of bankfull width was problematic because of the lack of clear banks resulting from the discontinuous nature of the reaches. In many of the reaches, bankfull width was most likely underestimated owing 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. Judging the magnitude of these potential measurement errors is difficult as they were not systematic and varied according to location. Bankfull distances may have been underestimated by as much as 0.5 m because of

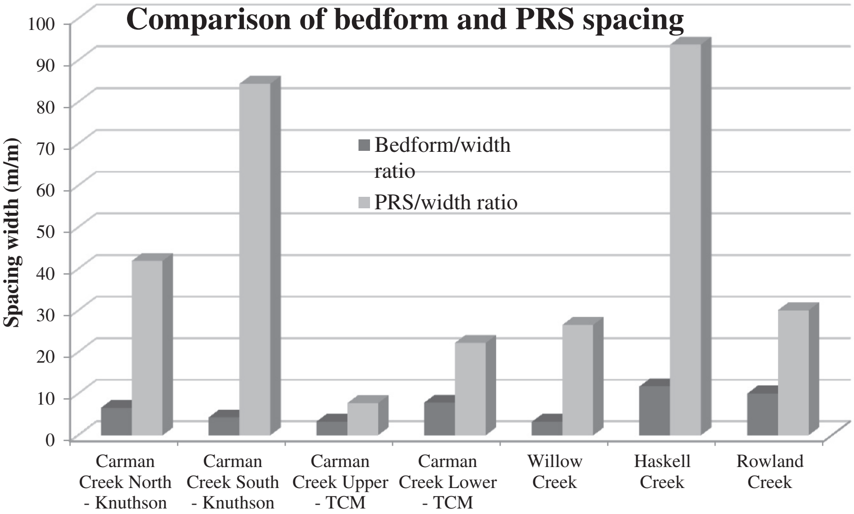

Fig. 7. Comparison of bedform and PRS to channel width ratio for each reach. PRS/width ratios far exceed bedform/width ratios because of the limited number of pool–riffle sequences in the meadow streams. Bedform/width spacing is much more consistent across reaches.

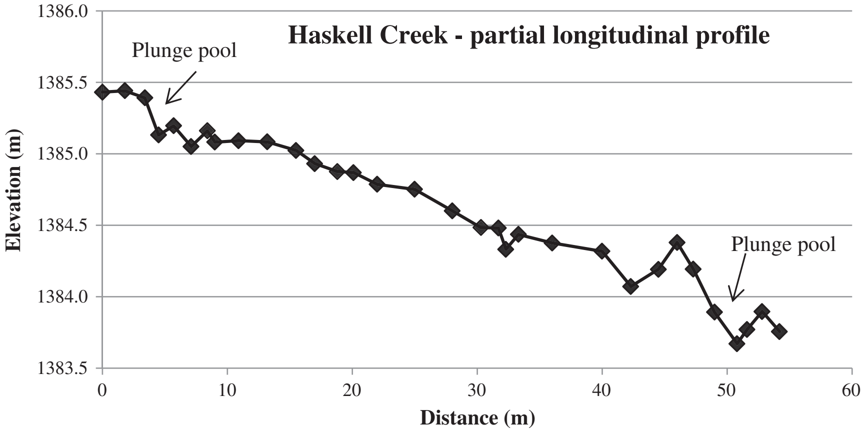

Fig. 8. Partial longitudinal profile of Haskell Creek showing the location of plunge pool headcuts that are deepening the channel.

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 owing 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. 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.

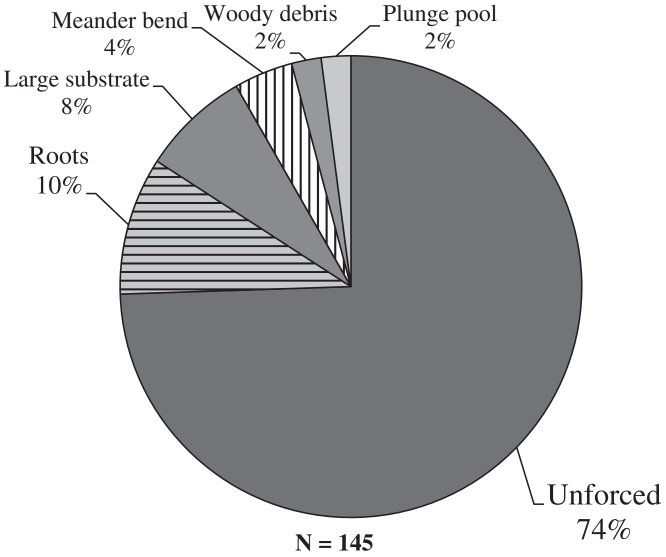

Fig. 9. Mechanisms causing the formation of pools in the study reaches. Unforced pools are most common, followed by forced pools of various causes.

4. Discussion

Despite limiting our sample set to channels developed on meadows with significant sod development in smaller watersheds, we observed a high variance in channel morphometric measures, especially in planform. Although the sample set was comprised of small channels, we found a continuum ranging from incipient, vegetation-controlled channels with characteristics of intermittent scouring in sod to alluvial channels containing grass sod steps similar to riffles. This observed channel development continuum is also dependent on watershed area and precipitation. The combination of factors in these systems provides

Fig. 10. A scour pool caused by extensive tree roots in Carman Creek, Three Corner Meadow.

Fig. 11. Headcut step in sod creating a plunge pool in Haskell Creek. Gray arrow indicates flow direction.

examples of biogeomorphic processes highly influenced by vegetation and substrate patterns.

We experienced the greatest amount of variation in the planform measurements of ratio of curvature and meander wavelength. Especially with these small channels, local controls caused by vegetation patterns appear to play a major role in influencing planform measures. Herbaceous vegetation can stabilize lateral channel movement and prevent bank erosion (Trimble, 1997; Micheli and Kirchner, 2002), yet abundant evidence, including experimental data (Braudrick et al., 2009), demonstrates the positive connection between vegetation and meandering: meanders do not appear to develop in streams without vegetated banks. The only exception to a high r_m/w is Carman Creek upper in Three Corner Meadow that had a smaller value (1.77) than the Leopold and Wolman (1960) standard. This reach is located under 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 focus bank erosion (or limit sod development) to create smaller bends. The restored reaches (Carman Creek and Haskell Creek) had the largest r_m/w values, which may be indicative of channels continuing to adjust to the restoration activities. These findings provide evidence for a continuum of channel development conditions related to r_m/w values, ranging from the highest in Carman Creek, a small watershed in a sod- and vegetation-controlled environment, to the lowest r_m/w values in Haskell and Rowland Creeks, which have the highest sinuosity and more of an alluvial system with deposits of gravels and cobbles. The observed gradient of meander patterns may have important implications for biogeomorphic processes and habitat availability, relevant to restoration planning.

Fig. 12. Surveying a sod bridge in Rowland Creek. The white arrow indicates the top of the bridge; the gray arrow indicates flow direction.

Similarly, normalized meander wavelength varied widely, though tending much higher than is typical for alluvial channels, and some sites had greater than expected length of straight reaches. Because the 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). For planform morphometry in general, apparently watershed and environmental variables such as basin size and precipitation/snowmelt regime may play a major part in influencing stream power and sediment input. Within that environmental framework, local controls such as woody vegetative cover and boulders or bedrock outcrops also contribute. Time is likely also a factor, but 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.

4.1. Bedforms

Typical pool–riffle sequences are 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 instream obstructions such as roots or large substrate. These pools tend to be connected by stretches of resistant grass sod that approximates the function of riffles by providing an energy-drop mechanism. For channels developing in meadows adjusting to pond-and-plug restoration, these bedforms may indicate an early stage in the continuum of channel development. As with planform features, a gradient of bedform features is apparent in the meadow channels, from the small, incipient channel of Carman Creek to the larger Rowland Creek system with perennial flow, bridges, and piping.

Despite the apparent differences, the presence of grass sod serves a similar energy-drop function between pools, similar to riffles in larger alluvial streams. As with planform characteristics, bedforms can be defined on a gradient ranging from small, sod, and vegetation-controlled channels with less-developed cyclic bedforms to larger alluvial channels with well-developed pools and riffles. Grass sod provides the energy-drop function in the smaller Carman Creek watershed, while scour holes serve the same purpose as steps or pools in the larger alluvial systems of Rowland and Haskell Creek. (Note that Haskell Creek, while having the smallest watershed area, has by far the highest basin precipitation, nearly twice that of Rowland, and thus had perennial flow at the sample site in contrast to Carman and Willow.) These scour holes were found at cyclic intervals, similar to typical pool–riffle systems. Our findings suggest that all of these are similar features on a gradient of possibilities.

The results show that bedforms, mainly pools, spaced within 5-7 channel widths are a consistent, cyclic phenomenon of these meadow channels. Instead of roughly equal numbers of pools and riffles, pools dominate the bedform pattern (at least based on the differencing technique) while remaining within the framework of 5-7 channel widths, similar to the pool–riffle cycle found in larger alluvial channels.

The bedform pattern may also be related to discontinuous gullies, a series of discrete scour holes separated by bare ground or vegetation and formed by headcut migration (Leopold and Miller, 1956). 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 and 3° (Eyles, 1977), associated with narrow channel width

(Leopold and Miller, 1956). Plunge pools deepen a discontinuous gully by undercutting during a storm flow, a feature evident in the meadow channels (Fig. 8). Hagberg (1995) found that headcut migration caused by plunge pools are the dominant erosional process in Sierra meadow streams. Discontinuous channels described by Bull (1997) are also similar in dimension but are described as having channels separated by fans and appear to be more alluvial in nature than our smaller channels. The observed meadow pools were located in intermittent scoured sections, with plunge pools forming below the sod riffle in some cases. The evidence shows that these scour holes may be cyclic and form as a result of the unique environmental factors acting on the meadow channels.

The nature of the bedforms, especially grass sod 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. Additional sites should be examined to interpret the linkage between discontinuous gullies and the bedform features found in the meadow channels, particularly in post-restoration sites.

5. 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 energy drops composed of grass sod instead of coarse-sediment riffles, connecting a series of pools along the channel bed. 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 population for comparison: the meadow streams contained larger bend radii and meander wavelengths and longer straight reaches. This type of channel morphology may be indicative of relatively rapid changes leading up to more well-developed forms or may already be in a form appropriate for a meadow with limited flows and substantial sod cover. Factors contributing to nonstandard planform morphology include extensive herbaceous vegetation with dense root masses that limit channel movement and prevent significant bank erosion.

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, with increasing similarity as we move to larger watersheds and/or greater precipitation and runoff. 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.

The combination of shallow gradients, resistant sod, and streamside obstructions (boulders and woody debris) caused extensive pool formation in these meadow channels. The environmental factors leading to pool creation have important implications for physical habitat that should be considered when planning meadow restorations (Montgomery et al., 1995; Gurnell and Sweet, 1998). As we further develop this understanding by repeat surveys and additional sites, land managers can use it 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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