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Cold Regions Research and Engineering Laboratory

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Channel Classification across Arid West Landscapes in Support of OHW Delineation

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Abstract

The Arid West region is dominated by watersheds that have a high frequency of intermittent and ephemeral channels. These channels are influenced by watershed characteristics and the local hydrologic regime, which dictate the amount of sediment deposited and eroded in the channel. Over time, this sediment movement causes the geometry of the channel and the surrounding floodplain to evolve. For this study, 14 mountain, 18 foothill, and 17 basin ephemeral and intermittent channels within multiple watersheds were evaluated for specific characteristics, including geology, slope, watershed design, and floodplain geomorphology. We used multivariate analyses to explore patterns of similarities and differences among the channel and watershed characteristics. Using these results and characteristics, we devised a simple, artificial channel classification to evaluate OHW indicators to better understand watershed and intermittent and ephemeral channels across the landscape in the Arid West region. A total of 18 channel types were classified: 4 in the mountains, 8 in the foothills, and 6 in the basins. Our findings demonstrate that watershed and channel characteristics vary considerably across the landscape in the Arid West, suggesting that channel classification is potentially useful for evaluating the variability of occurrence of OHW indicators at a larger scale.

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Preface

This research was funded by the Wetland Regulatory Assistance Program (WRAP), Headquarters, US Army Corps of Engineers.

The principal investigators were Lindsey Lefebvre, Robert W. Lichvar, Katherine Curtis, and Jennifer Gillrich, all of the Remote Sensing/ Geographic Information Systems (RS/GIS) and Water Resources Branch, Cold Regions Research and Engineering Laboratory (CRREL), US Army Engineer Research and Development Center (ERDC), Hanover, NH.

Robert Lazor, Environmental Laboratory, ERDC, Vicksburg, MS, and Dr. Mark Sudol, Institute of Water Resources, US Army Corps of Engineers, Washington, DC, are recognized for their early foresight and interest in pursuing OHW research in the western United States in support of the Corps Regulatory Program. Since then, both Meg Gaffney-Smith and Karen Mulligan of the Headquarters Regulatory Program have continued an interest in and funding for pursuing this important effort to support western Corps Districts.

This study was conducted under the general supervision of Timothy Pangburn, Chief, RS/GIS and Water Resources Branch; Dr. Justin B. Berman, Chief, Research and Engineering Division; Dr. Lance Hansen, Deputy Director; and Dr. Robert E. Davis, Director. Permission to publish was granted by the Director, Cold Regions Research and Engineering Laboratory.

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1 Introduction

Arid West fluvial systems are regulated as "Waters of the United States" (WoUS) under Section 404 of the Clean Water Act. The jurisdictional limits in Arid West channels are defined by using the "ordinary high water mark" (OHWM). The OHW boundary is defined in 33 CFR Part 328.3 "as a line on the shore established by fluctuations of water and indicated by physical characteristics such as clear, natural line impressed on the bank, shelving, changes in the character of the soil, destruction of terrestrial vegetation, or the presence of litter and debris." The Arid West region is dominated by watersheds that have a high frequency of intermittent and ephemeral channels (Field and Lichvar 2007), and the OHW boundary is determined by observing recent physical evidence subsequent to flow. Channel morphology and physical features associated with the OHWM are frequently the result of low to moderate floods or short-term, high-intensity events characteristic of the climate in the Arid West (Graf 1988; Tooth 2000).

Intermittent and ephemeral channels in the Arid West have three hydrogeomorphic surfaces: the low-flow channel, the active channel, and the floodplain (Fig. 1). Previous Arid West OHW studies (Lichvar et al. 2006, 2009) reported that intermittent and ephemeral channels generally do not have separate bankfull and active channels. Instead, they are combined to make one active channel where the majority of erosion and sedimentation occurs (Lichvar and McColley 2008). Lichvar et al. (2009) reported that the position of the bankfull channel (based on the concept of a recurrence interval of 1.5–2 years) is unstable and frequently changes during and after various flow events. In essence, the bankfull channel represents a low-flow channel within the active channel. The outer limit of the active channel remains more stable over time and represents the lateral extent of the OHWM (Lichvar et al. 2009). In light of the flashy and dynamic nature of these channels, the active channel captures the regulatory intent of the "ordinary high water mark."

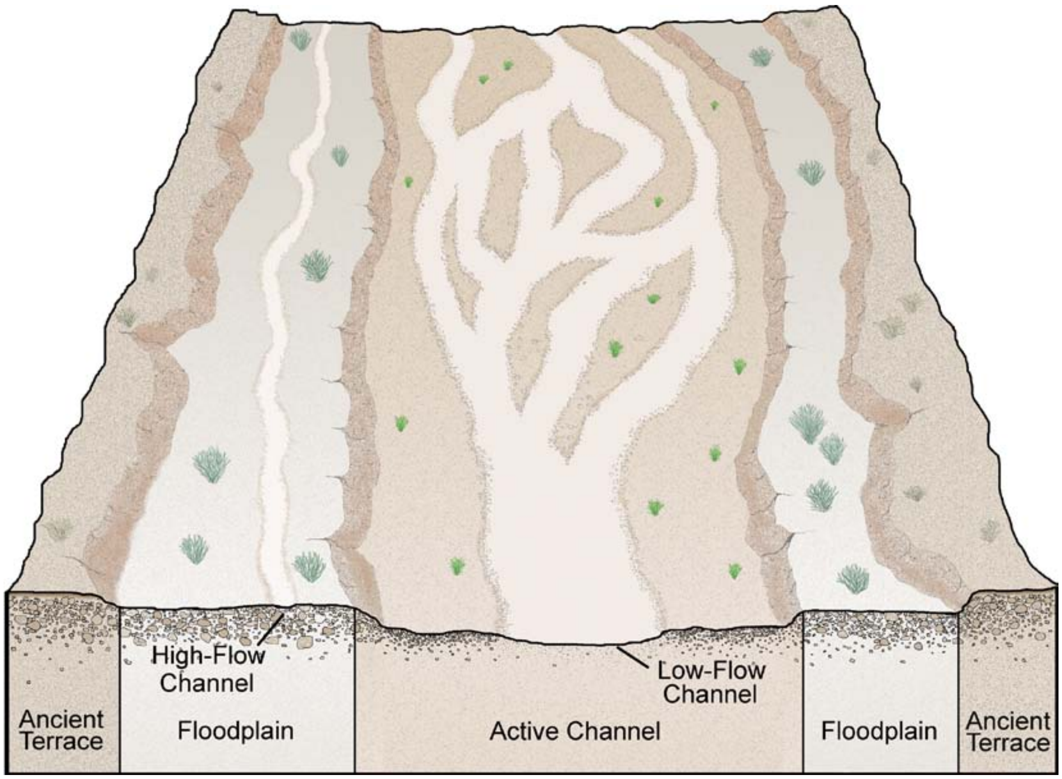

Figure 1. Hydrogeomorphic floodplain units for a typical Arid West channel.

Intermittent and ephemeral channel types found in the Arid West include single-thread channels, compound channels, discontinuous ephemeral channels, alluvial fans, and anastomosing channels. These channel types are influenced by watershed characteristics and the local hydrologic regime, which dictate the amount of sediment deposited and eroded in the channel. The deposition and erosion of the channel cause the geometry of the channel and the surrounding floodplain to evolve over time (Lichvar and McColley 2008). Because channel types have pronounced spatial and temporal variability in channel morphology, physical features found along a channel vary between types, along the length of any given stream, and through time at a single point (Field and Lichvar 2007).

Understanding the processes and characteristics of channels requires knowledge of their natural hierarchical structure based on channel morphology and physical features (Rosgen 1996). The geomorphology of Arid West channels reflects the impacts of the environmental influence through climate, topography, and vegetation responses, which vary across the region (Kingsford 2006). Watershed characteristics, such as lithology, slope, and the local hydrologic regime, also influence channel conditions and the surrounding floodplains. To understand watershed and channel characteristics in the Arid West region, we developed an artificial channel classification scheme to support OHW delineations based on three landscape positions: mountains, foothills, and basins. To provide data for creating the classification, we visited 49 Arid West sites and evaluated them for specific characteristics, including geology, slope, watershed shape, and floodplain geomorphology.

2 Site Descriptions

We sampled 49 ephemeral and intermittent channels throughout the Arid West region, chosen to represent channels in various landscape positions, in 2006 through 2009. Of the 49 sites, 14 were in the mountains, 18 in the foothills, and 17 in the basin (Fig. 2). All were in separate watersheds.

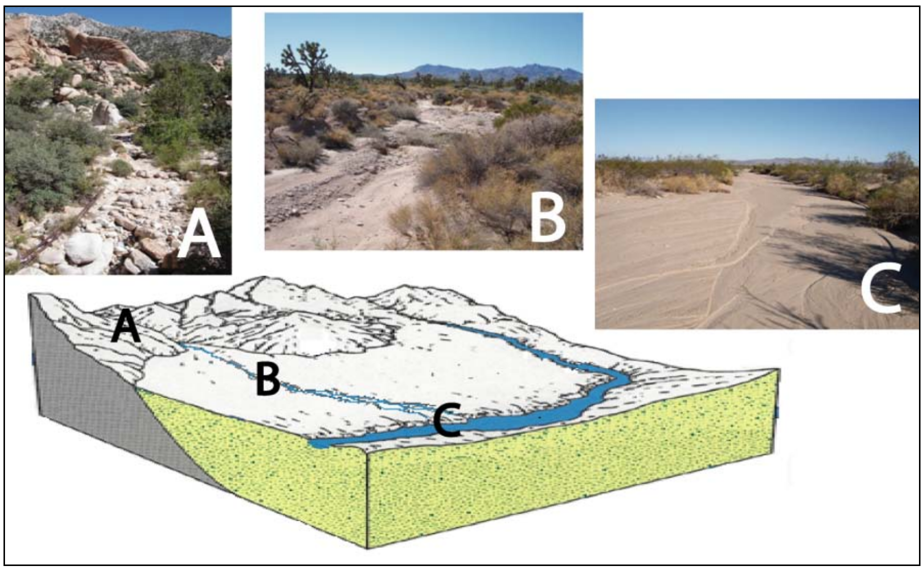

Figure 2. Diagram of landscape positions visited along a channel (A: Mountains, B: Foothills, C: Basin).

When choosing the watershed sites, we looked for those that had minimal anthropogenic influences to ensure that channel responses and physical characteristics were the result of natural processes and not human influence. Figure 3 shows the site locations. Each point on the map represents a gauged channel and corresponds to multiple site locations within the gauged watershed. Table 1 lists the site locations in Figure 3 and gives the number of sites at each location and the corresponding landscape position. Watersheds were spread across multiple Bailey's eco-regions, including Mediterranean Division, Mediterranean Regime Mountains, Tropical/Subtropical Desert Division, Tropical/Subtropical Regime Mountains, Tropical/Subtropical Steppe Division, and Temperate Desert Division (Bailey 1995).

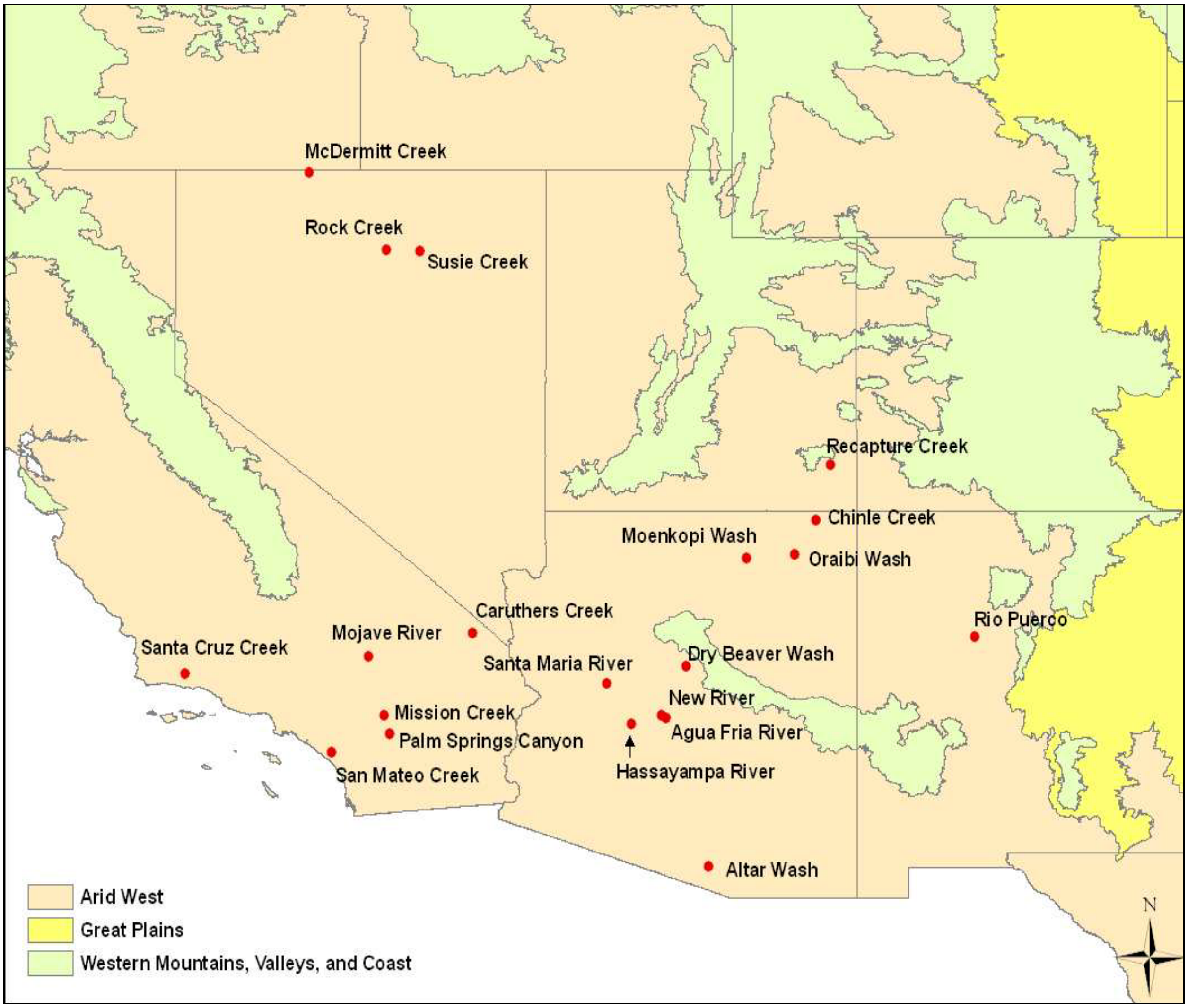

Figure 3. Site locations in the Arid West region. Red dots represent general locations of watersheds sampled.

Table 1. Site locations shown in Figure 3, with the number and location of landscape positions sampled at each point.

Site Locations	Number of Positions Sampled	Location of Landscape Position
Agua Fria River, AZ	3	Mountain, Foothill, Basin
Altar Wash, AZ	2	Foothill, Basin
Caruthers Creek, CA	3	Mountain, 2 Basins
Chinle Creek, AZ	3	Mountain, 2 Basins
Dry Beaver Wash, AZ	2	Mountain, Foothill
Hassayampa River, AZ	1	Foothill
McDermitt Creek, NV	3	Mountain, Foothill, Basin
Mission Creek, CA	2	Foothill, Basin
Moenkopi Wash, AZ	3	Mountain, Foothill, Basin
Mojave River, CA	1	Basin
New River, AZ	3	Mountain, 2 Foothills
Oraibi Wash, AZ	3	Mountain, Foothill, Basin
Palm Canyon Wash, CA	3	Mountain, Foothill, Basin
Recapture Creek, UT	2	Mountain, Foothill
Rio Puerco, NM	3	Mountain, Foothill, Basin
Rock Creek, NV	1	Foothill
San Mateo Creek, CA	3	Mountain, Foothill, Basin
Santa Cruz Creek, CA	3	Mountain, 2 Foothills
Santa Maria River, AZ	3	Mountain, Foothill, Basin
Susie Creek, NV	2	2 Basins
Total	49	14 Mountain 18 Foothill 17 Basin

3 Methods

3.1 Background information

Prior to the field efforts, we collected and compiled preliminary information for each sample site, including hydrologic unit codes (HUC), channel data, and geologic data. This information provided guidance in selecting sites and classifying channel types. We also calculated watershed and channel characteristics, including drainage area, length of watershed, elevation difference of the principal flow path, watershed slope, basin shape factor, and drainage density. A multivariate analysis used these data to explore patterns of similarities and differences among the 49 channels.

The US Geological Survey divides the United States into hierarchical hydrologic units based on watersheds delineated using surface hydrologic features. Each hierarchical hydrologic unit is identified by a unique Hydrologic Unit Code (HUC) with six levels of classification and is defined in Table 2 (USDA 2007).

Table 2. Hydrologic Unit Code (HUC) descriptions.

Levels	Hydrologic Unit Code (HUC)	Classification
First	2-Digit	Region
Second	4-Digit	Sub-Region
Third	6-Digit	Accounting Unit
Fourth	8-Digit	Cataloging Unit
Fifth	10-Digit	Watershed
Sixth	12-Digit	Sub-Watershed

For each site, we obtained and downloaded all HUCs as a single shapefile from the US Department of Agriculture Geospatial Data website (USDA 2010). Sample site selection began with identifying a gauged ephemeral or intermittent channel within an 8-digit HUC in the Arid West region. We analyzed the gauge data to confirm that the channels were ephemeral or intermittent (Curtis et al. 2011). Within each of the twenty 8-digit HUCs, we chose sample locations for the three landscape positions—mountain, foothill, and basin—based on the stream order, the availability of topographic maps and aerial photography, and the amount of anthropogenic disturbance (Fig.). In 11 of the 8-digit HUCs, not all three landscape positions were visited due to accessibility and time constraints. Therefore, to increase the sample size, two locations in the same landscape position were visited in five watersheds. To decrease the variability of characteristics found within an 8-digit HUC (Fig. 4), each landscape position was located within a separate smaller 12-digit HUC. The smaller-scale HUC allowed for a more localized relationship of physical features to channel features in each of the landscape positions.

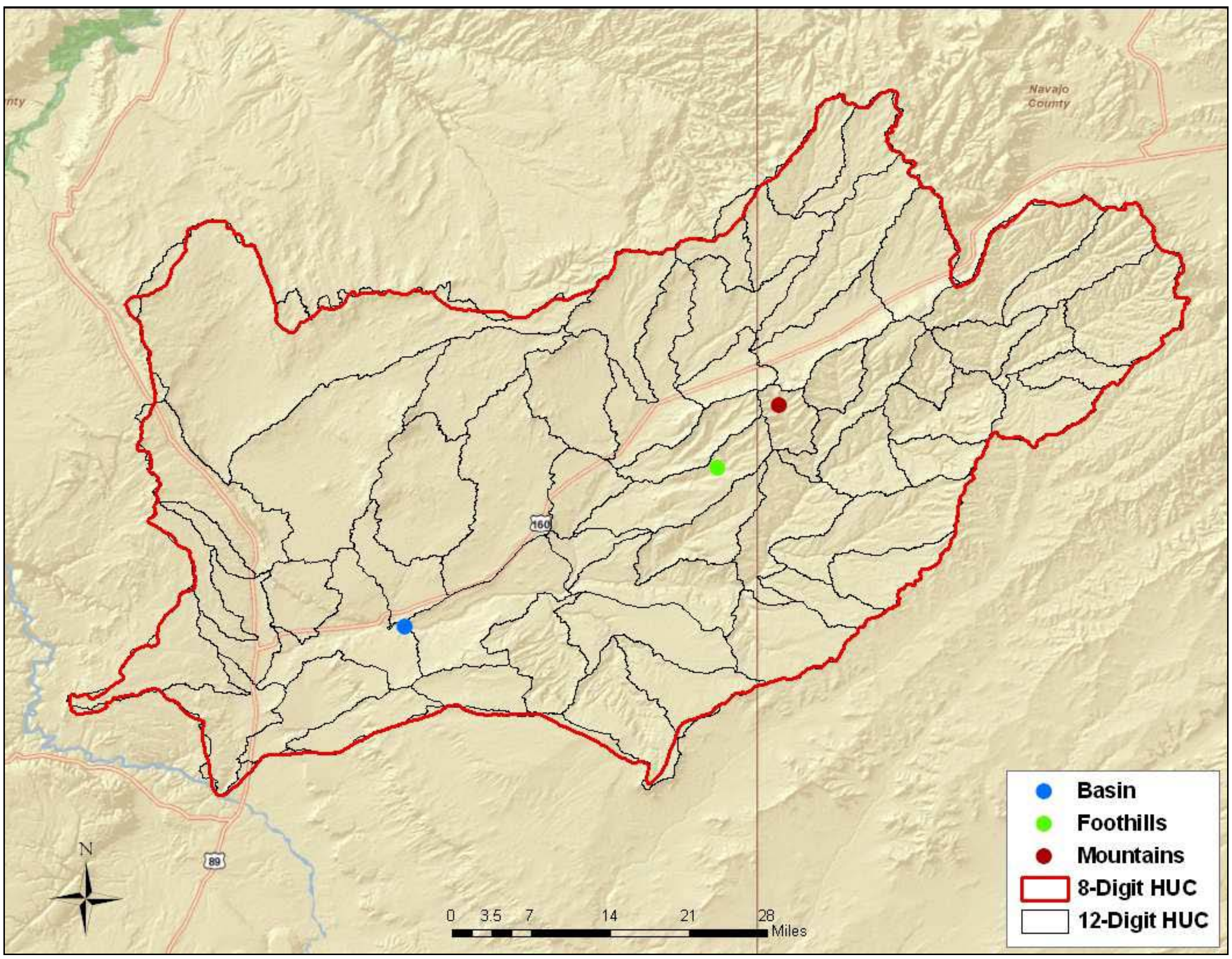

Figure 4. Example of site selection within an 8-digit Hydrologic Unit Code (HUC) and the landscape-based field sites located within 12-digit HUCs.

We downloaded GIS data from multiple sources for each 12-digit HUC and obtained from the US Geological Survey digital stream channel data from the National Hydrography Dataset (NHD) (USGS 2010). The NHD digital stream data were downloaded as a line shapefile showing streams and small rivers, along with water flow through lakes and larger rivers (USGS 2010). Figure 5 shows an example. Multiple calculations of channel and watershed characteristics used the digital stream data (Table 3). On the 12-digit HUC watersheds, we overlaid a generalized geologic map of the contiguous US, obtained from the US Geological Survey (2006). The map shows major geologic units in the US that represent the geology of the bedrock that lies at or near the surface, but it does not indicate surficial materials such as soils, alluvium, or glacial deposits (USGS 2006). We used this layer to determine whether each watershed's geology was hard rock or soft rock.

Table 3. Calculations and implications for watershed characteristics.

Calculation	Formula	Variables	Implications
Watershed slope	$S = DE/L$	S: Watershed slope DE: Difference in elevation between the two end points of the principal flow path L: Hydrologic length of the principal flow path	4–10% = Steep slope 2–4% = Moderate slope < 2% = Shallow slope
Basin shape factor	$SH = DA/L^2$	SH: Basin shape factor DA: Drainage area L: Hydrologic length of the principal flow path	< 0.14 = Elliptical watershed 0.15–0.24 = Oval watershed > 0.25 = Circular watershed
Drainage density	$DD = L_t/DA$	DD: Drainage density L_t: Total length of all streams within a watershed DA: Drainage area	> 1 = Highly dissected watershed: Finely divided network of streams with short lengths and steep slopes (Gordon et al. 2004) 0.5–1 = Moderately dissected watershed < 0.5 = Low dissected watershed: Less strongly textured, stream lengths longer, valley sides flatter, and streams farther apart (Gordon et al. 2004)

Lastly, using ArcMap 9.2, we calculated multiple watershed characteristics, including drainage area, length of watershed, elevation difference of the principal flow path, watershed slope, basin shape factor, and drainage density using the 12-digit HUC watershed and the NHD stream data. We determined drainage area from the 12-digit HUC data included in the shapefile for each site. The length of watershed was equivalent to the length of the principal flow path, which is the distance traveled by the surface drainage from the watershed boundary to the watershed outlet (Fig. 5). If the channel did not extend to the boundary of the watershed, the line was extended from the end of the channel to the watershed boundary. We also calculated elevation difference from the principal flow path by determining the elevation difference between the highest point on the principal flow path and the watershed outlet (Fig. 6). Table 3 lists the calculations used for watershed slope, basin shape factor, and drainage density of a watershed and what the results imply for watersheds.

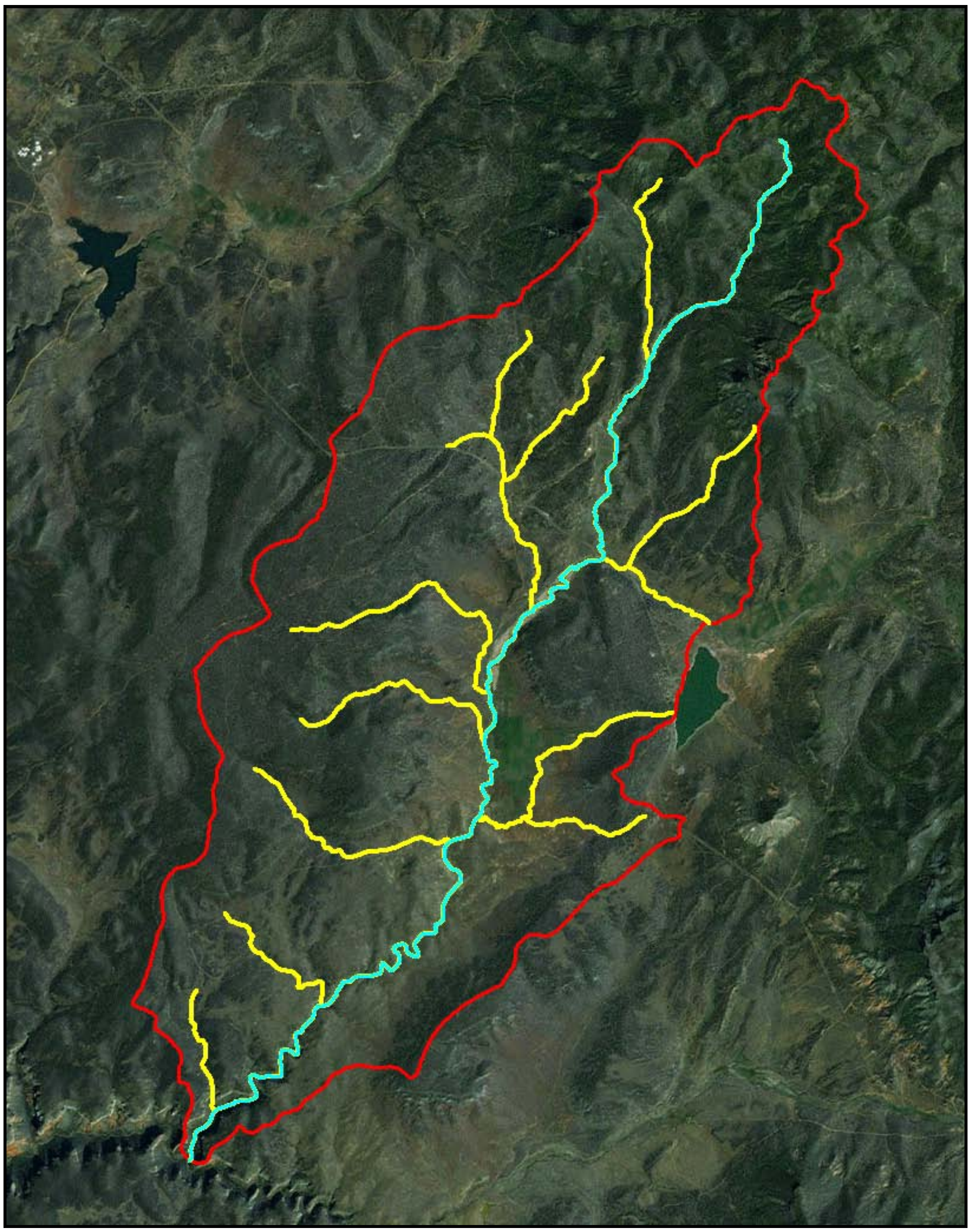

Figure 5. National Hydrography Dataset for Chinle Creek, AZ (red: boundary of watershed; yellow: stream channel data; blue: principal flow path).

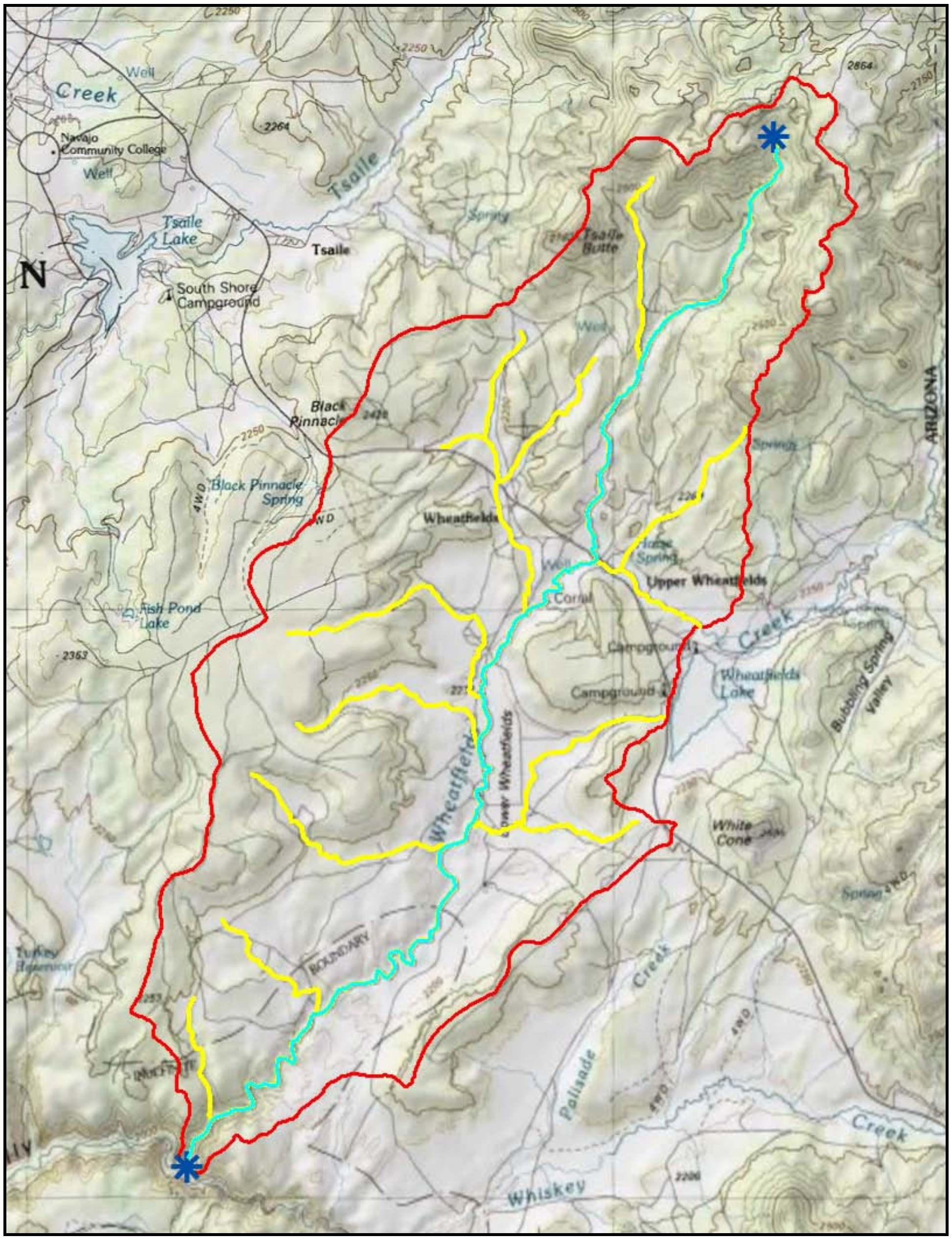

Figure 6. Example of elevation difference determined from the principal flow path at Chinle Creek, AZ (red: boundary of watershed; yellow: stream channel data; blue: principal flow path; blue stars: highest and lowest points of the principal flow path).

3.2 Site visits

We conducted three trips throughout the Arid West region for field visits: in August 2006, July 2009, and September 2009. In each watershed, we collected and recorded data for both the active channel and the floodplain, including a brief site description with any further information regarding landscape and geology, channel morphology, presence or absence of disturbance, evidence of aggredation and degradation, land use condition, width and depth of channel, channel and floodplain texture, vegetation cover, species richness, and plant structure. Table 4 lists the number of channel types visited across the Arid West landscape.

Table 4. Number of channel types visited across the mountain, foothill, and basin landscape positions in the Arid West region.

Channel type	Mountains	Foothills	Basin
Single thread	14	5	4
Compound	0	12	10
Discontinuous ephemeral	0	1	3
Total	14	18	17

3.3 Data analysis

We used multivariate analyses to explore patterns of similarities and differences among the channels. To explore relationships among channels based on channel and watershed (12-digit HUC) characteristics, we created a main data matrix of 49 channels × 8 quantitative variables: channel width, channel depth, drainage area, basin shape factor, principal stream length in the 12-digit HUC, length of all streams in the 12-digit HUC, elevation difference along the principal flow path, and drainage density. We log-transformed the data to improve normality and relativized them by their standard deviations so that no variable would exert excessive influence on the analysis (McCune 1988). McDermitt Creek, NV, (basin) (W46) was identified as an outlier and removed from the main matrix (Table 5). We created a secondary matrix composed of 48 channels × 5 categorical variables (landscape position, geology, channel morphology, active channel sediment texture, and terrace sediment texture) to explore differences among the channels. Each of these variables was composed of several classes (Table 6).

We used principal components analysis (PCA) and PC-ORD 5.14 software (McCune and Mefford 2006) to examine patterns of similarities and differences among the channels. PCA is a data reduction technique that we used to condense the quantitative variables into two components that best explained the relationships among the channels. Significant components were those that explained more variation in the data than would be expected by chance. The eigenvalues of significant components were smaller than those of a broken-stick model (McCune and Grace 2002). In the ordination diagram, we arranged the 48 channels on the two components (axes), which represented the most influential variables from the main matrix. Adjacent channels were more similar than channels that were farther apart. We superimposed each categorical variable separately over the arrangement of channels to examine patterns among its classes.

Table 5. List of channels and the abbreviations used to identify them in the principal components analysis ordination. W46 was identified as an outlier and was excluded from the analyses.

Number	Name	Number	Name
W1	Caruthers Creek, CA (mountain)	W26	Oraibi Wash, AZ (foothill)
W2	San Mateo Creek, CA (mountain)	W27	Santa Cruz Creek, CA (lower foothill)
W3	New River, AZ (mountain)	W28	Santa Cruz Creek, CA (upper foothill)
W4	McDermitt Creek, NV (mountain)	W29	Dry Beaver Wash, AZ (foothill)
W5	Agua Fria River, AZ (mountain)	W30	Recapture Creek, UT (foothill)
W6	Santa Maria River, AZ (mountain)	W31	Hassayampa River, AZ (foothill)
W7	Rio Puerco, NM (mountain)	W32	Altar Wash, AZ (basin)
W8	Santa Cruz Creek, CA (mountain)	W33	Mission Creek, CA (basin)
W9	Dry Beaver Wash, AZ (mountain)	W34	Caruthers Creek, CA (basin)
W10	Chinle Creek, AZ (mountain)	W35	Santa Maria River, AZ (basin)
W11	Recapture Creek, UT (mountain)	W36	Mojave River, CA (basin)
W12	Palm Canyon Wash, CA (mountain)	W37	Palm Canyon Wash, CA (basin)
W13	Oraibi Wash, AZ (mountain)	W38	Caruthers Creek, CA (lower basin)
W14	Moenkopi Wash, AZ (mountain)	W39	San Mateo Creek, CA (basin)
W15	Rock Creek, NV (foothill)	W40	Chinle Creek (lower basin)
W16	Agua Fria River, AZ (foothill)	W41	Chinle Creek (middle basin)
W17	Santa Maria River, AZ (foothill)	W42	Altar Wash (middle basin)
W18	New River, AZ (lower foothill)	W43	Susie Creek, NV (lower basin)
W19	New River, AZ (upper foothill)	W44	Susie Creek, NV (middle basin)
W20	Mission Creek, CA (foothill)	W45	Oraibi Wash, AZ (lower basin)
W21	Palm Canyon Wash, CA (foothill)	W46	McDermitt Creek, NV (basin)
W22	Rio Puerco, NM (foothill)	W47	Agua Fria, AZ (basin)
W23	Moenkopi Wash, AZ (foothill)	W48	Rio Puerco, NM (basin)
W24	McDermitt Creek, NV (foothill)	W49	Moenkopi Wash, AZ (basin)
W25	San Mateo Creek, CA (foothill)		

Table 6. Five categorical variables and their component classes used to classify Arid West channels.

Categorical variable	Component classes
Landscape Position	Mountain Foothill Basin
Geology	Hard Rock Hard/Soft Rock Soft Rock
Channel Type	Compound Single Thread Discontinuous Ephemeral
Active Channel Texture	Silt Sand Gravel Cobble Boulders
Terrace Texture	Silt Sand Gravel Cobble Boulders

3.4 Preliminary results

Overall, there were very few patterns in the Arid West channel data. The PCA produced a scattering of points that lacked discrete groups (Fig. 7). The 48 channels were arranged based on two components. The first was a combination of principal stream length and drainage area. Channels on the left side of the ordination were located in 12-digit HUCs that drained larger areas and contained longer principal streams. Channels on the right side of the ordination diagram were located in 12-digit HUCs that drained smaller areas and had shorter principal streams. Component loadings confirmed that both principal stream length (−0.88) and drainage area (−0.87) decreased from left to right along axis one. These physical characteristics were the most important components of the axis, which represented 45.2% of the variation in the channel data.

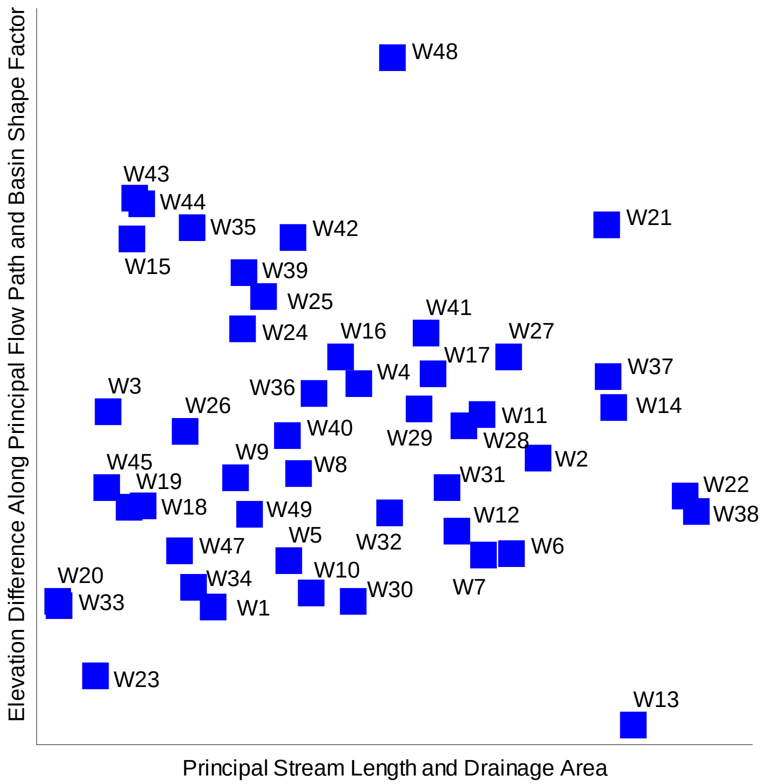

Figure 7. Principal components analysis of 48 Arid West channels. Adjacent channels are more similar than widely spaced channels. Along axis one, values decrease from left to right. Along axis two, from bottom to top, elevation differences decrease and basin shape factors increase from elliptical to circular. Channel placement on the first two components (axes) represents 60.6% of the correlation structure among channels and 69.1% of the variation in the data. Table 5 is a key to the channel names.

The second component was a combination of two watershed characteristics: basin shape factor and elevation differences along the principal flow path. Channels near the top of axis two were located in 12-digit HUCs characterized by little change in elevation along the principal flow path and more circular basin shapes. In contrast, channels at the bottom of axis two were located in elliptical basins characterized by large differences in elevation from the source of the principal flow path to its outlet. Component loadings confirm that elevation differences along the principal flow path (−0.73) decreased from the bottom to the top of axis two, and basin shape increased from elliptical to oval to circular (0.67). These two variables were the most important components of axis two, which represented 23.9% of the variation in the data. Overall, channel placement on the first two components (axes) represented 60.6% of the correlation structure among channels and 69.1% of the variation in the data.

Few patterns were evident when we superimposed each categorical variable on the ordination (Fig. 8). With regard to landscape position, mountain channels were restricted to the bottom half of the diagram. These mountain channels typically had larger elevation differences from source to outlet and were elliptical to oval in shape (Fig. 8a). Basin channels were most prevalent on the left side of the ordination, suggesting that they were located in 12-digit HUCs with long principal streams that drained large areas. Foothill channels occurred throughout the diagram, suggesting there is no pattern based on these eight quantitative variables.

Arid West channels were equally likely to be underlain by hard rock, such as granite or gneiss, or soft rock, such as sandstones and sedimentary rocks, regardless of differences in stream length, drainage area, watershed shape, and elevation differences (Fig. 8b). Because there were only two channels composed of both hard and soft rock, no pattern was evident. There also was no pattern with regard to channel morphology. Compound and single-thread channels were distributed throughout the diagram (Fig. 8c). Discontinuous ephemeral channels appeared restricted to circular and oval basins with long principal streams that drained large areas (W26, W43–W45). However, more data are necessary to confirm this trend as the number of discontinuous ephemeral channels in this study was small ($n = 4$).

With regard to active channel texture, boulder- and boulder/cobble-dominated channels occupied oval basins with moderate elevation differences along the principal flow path. These channels were located mainly in the center of the ordination (W8, W17, W27, W28) (Fig. 8d). Boulders never dominated the channels from circular basins with slight elevation differences (at the top of the diagram). Cobble-, sand-, or silt-dominated channels occurred throughout the ordination, regardless of differences in drainage area and stream length or in basin shape and elevation.

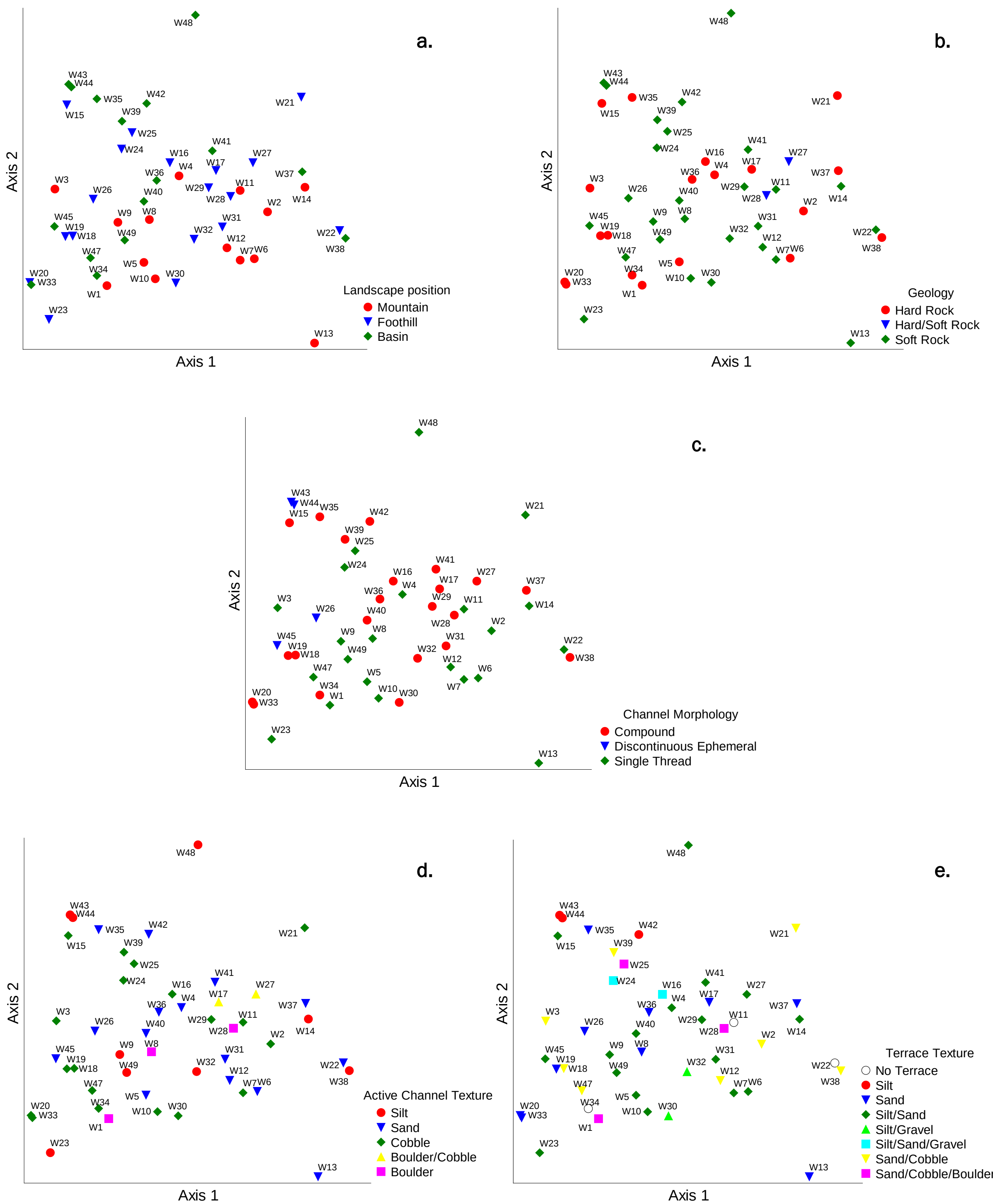

Figure 8. Principal components analysis of Arid West channels overlain by five categorical variables. The axes represent the same components as in Figure 7. On axis one, principal stream length and drainage area decrease from left to right. On axis two, from bottom to top, elevation differences decrease and basin shape factors increase from elliptical to circular. Table 5 is a key to the watershed names.

There were few patterns with regard to terrace sediment texture. Three silt-dominated terraces had only circular watersheds characterized by little difference in elevation, in which long principal streams drained large areas. However, sand, cobbles, or boulders also dominated these channels in the upper left corner of the diagram (Fig. 8e). The data suggest that the dominant sediment size on terraces was variable, ranging from sand to boulders, despite differences in drainage area and stream length or in basin shape and elevation.

Overall, the ordination diagram of Arid West channels showed an amorphous scattering of points, suggesting a continuous gradient of physical characteristics (Fig. 7). Discrete clusters or groups of channels were not apparent. Distinct groups might have suggested that the channels could be clearly separated and classified based on the quantitative variables or the classes of categorical variables or both. Although the data show trends with regard to landscape position and active channel sediment type, there are no other discrete groups or clusters upon which an observation-based classification system can be based. Therefore, we propose an artificial classification for Arid West channels.

3.5 Channel classification in support of OHW delineations

Many geomorphic river classification schemes for channels have been developed and are used for scientific understanding of how rivers function and for river management purposes, including channel maintenance, improvement, restoration, and conservation (Kondolf et al. 2003). Because of the diversity and dynamics in channels, no single classification satisfies all needs or includes all channel types; each classification has advantages and disadvantages for use in geological and ecological applications (Montgomery and Buffington 1997). The various classifications differ in intended purpose, approach, disciplines involved, and characteristics of the systems being classified (Kondolf et al. 2003). They use different variables and spatial scales, making each unique for its intended purpose. For example, Davis (1899) and Strahler (1957) both described valley geomorphology and quantified drainage network at a basin scale, Leopold and Wolman (1957) described alluvial channel patterns, and Petit (1995) and Rosgen (1996) described channel morphology and dynamics at a channel reach scale.

Some of the earliest forms of channel classification were based on distinctions between mountain and lowland channels (Dana 1850, Powell

1875). Channel classifications from New Zealand (Nevins 1965) and Washington state (Palmer 1976) have also recognized that channels vary in a longitudinal direction and have identified distinct zones on a channel with distinct gradient, channel pattern, valley cross section, and bed material size (Kondolf et al. 2003).

This classification hierarchy starts with three simple landscape features that are practical for OHW delineations. It was assembled by grouping watersheds based on similar characteristics and channel features in the Arid West region. Figure 9 outlines the classification. Each tier in the flowchart is color coded, and the colors are used throughout this report. The major characteristics used in this classification included the geology of the landscape position, the channel morphology, the average sediment texture size within the active channel, and the elevation difference in the watershed. The first tier of the flowchart is landscape position, followed by geologic rock type and then channel type.

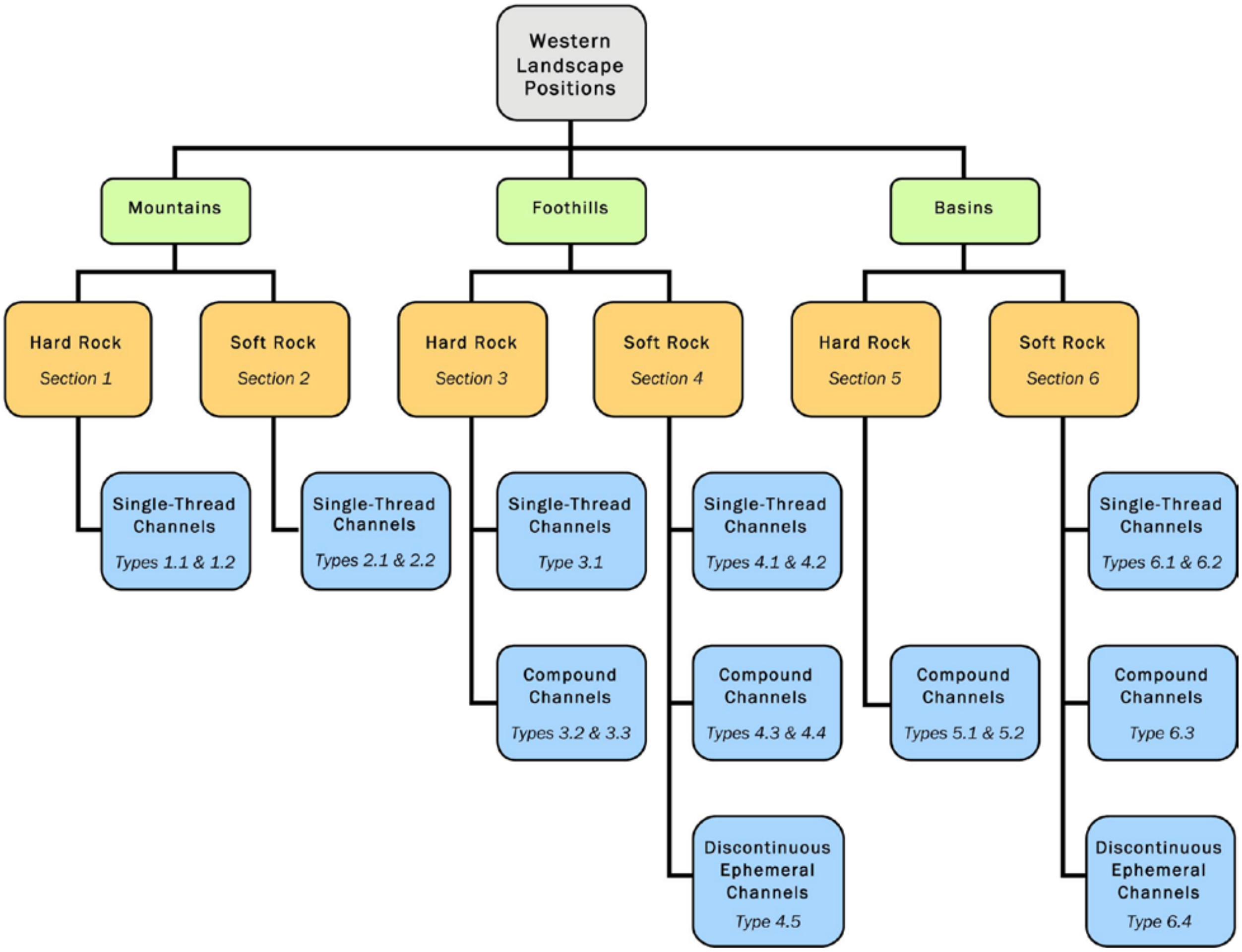

Figure 9. Channel classification for the Arid West region in support of OHW delineations (green: landscape position; orange: geology; blue: channel morphology).

Geology was the second characteristic used in classifying channels because of its influence on substrate resistance, channel width and depth, and bed gradient (Wohl and Achyuthan 2002). The geologic setting was divided into soft rock and hard rock because the two rock types are associated with different channel characteristics. Soft rock landscapes are typically associated with sandstones and sedimentary rock, and the channels tend to be less confined with highly erodible sediment. Hard rock areas, with granite, gneiss, or volcanic rock, are more stable and have more confined channels (Reid and Frostick 1997). Differences may exist between channel width and depth in hard and soft rock watersheds because width and depth can be explained in their relation to the nature of the local bank material (Murphey et al. 1972). Typically, narrow, deep channels are associated with sediments high in silt-clay, and channels containing coarser sediments are wide and shallow channels (Schumm 1961).

The third tier of the flow chart breaks the classification down by channel morphology: single-thread channels, compound channels, and discontinuous ephemeral channels. Both spatially and temporally, channel morphology and position are highly variable in the Arid West because of limited vegetation, unstable sandy banks, transmission losses, and high interannual variability in peak discharges (Lichvar and Wakeley 2004). Geology and soil are important variables affecting the size of sediment available and the processes that occur in Arid West channels, consequently influencing channel morphology.

Streambed material was the last characteristic used in our classification. Bed material gradually changes from cobble and boulders in the mountain channels to sand and gravel in the lowland rivers (Kondolf et al. 2003). Texture types in this classification included boulder, cobble, sand, and silt and are categorized in the classification as dominant texture in the active channel and in the floodplain. Dominant texture in the active channel and in the floodplain refers to the average sediment texture size in the channel, which is the dominant particle size of the floodplain unit and is described by Wentworth size classes (Curtis and Lichvar 2010).

4 Results

4.1 Mountains

Throughout the Arid West region, the channel morphology in mountain watersheds is less variable than in foothill and basin watersheds. Single-thread channels were the only channel type that was observed in both hard and soft rock watersheds. In hard and soft rock watersheds, two channel types can be identified based on the dominant texture in the active channel: boulder/cobble-dominated channels and sand/silt-dominated channels. Below is a list of observations for mountain channels in the Arid West region:

- Hard rock watersheds have moderate to steep slopes, whereas soft rock watersheds have shallow to steep slopes.
- The boulder/cobble-dominated channels tend to have pool-riffle morphologies, whereas sand/silt-dominated channels are more horizontal and planar.
- All mountain channels have sand-dominated floodplains.

Figure 10 shows the mountain channel classification. Figures 11 through 22 are examples of their respective categories.

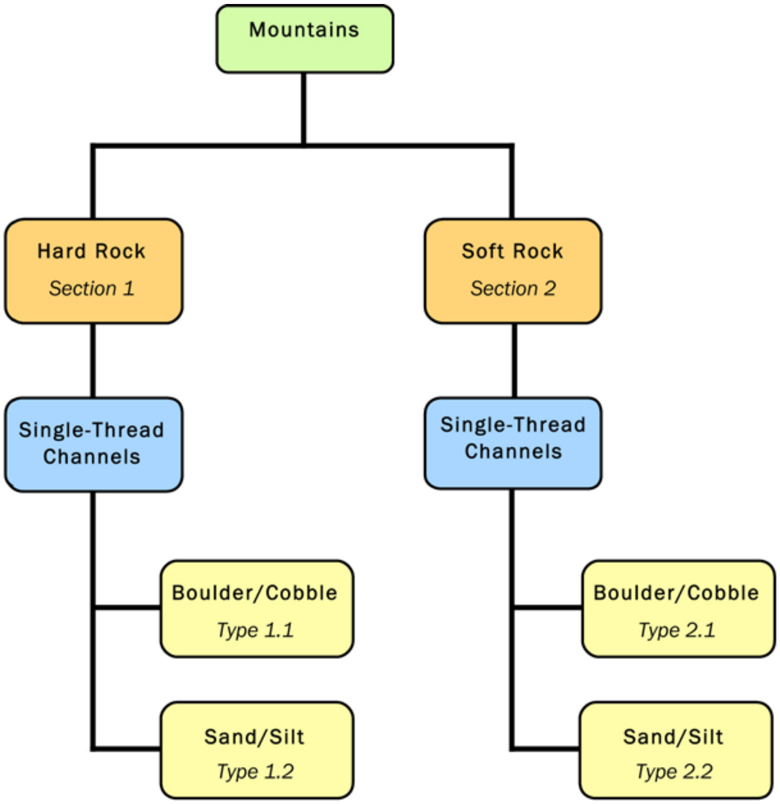

Figure 10. Classification of mountain channels in the Arid West region. In the following descriptions, headings for the orange boxes are bold, blue boxes bold italics, and yellow boxes italics.

Section 1. Mountain, Hard Rock Watersheds

Figure 11. Landscape perspective at Agua Fria River, AZ.

Figure 12. Landscape perspective at McDermitt Creek, NV.

Mountain, Hard Rock, Single-Thread Channels

Table 7. Characteristics of mountain, hard rock, single-thread channels.

Watershed and channel characteristics	Boulder/cobble-dominated active channel	Sand/silt-dominated active channel
Drainage area	> 100 km^2	< 100 km^2
Drainage density	Moderate	Moderate–high
Drainage shape	Elliptical–circular	Oval–circular
Elevation difference	< 1000 m	< 1000 m
Slope	Moderate–steep	Moderate–steep
Width	< 50 m	< 100 m
Depth	< 2.5 m	< 2 m
Dominant floodplain texture	Cobble and sand	Sand and silt
Site locations	Caruthers Creek, CA New River, AZ San Mateo Creek, CA	Agua Fria River, AZ McDermitt Creek, NV Santa Maria River, AZ

The dominant active channel texture of mountain, hard rock watersheds can be either boulder/cobble or sand/silt (Table 7). The two types have similar ranges of elevation difference within the watershed, and both have moderate to steep slopes. Boulder/cobble-dominated channels tend to have larger drainage areas and narrower channels (W1–W3) (Fig. 8a–d). They also exhibit the pool-riffle morphology that is common in humid regions because of the change in bed material size. The sand/silt-dominated channels tend to be horizontal and planar (W4–W6) (Fig. 8a–d). In terms of texture-size distribution, planar beds tend to be more responsive to changes in discharge or sediment supply than the step-pool channels (Montgomery and MacDonald 2002).

Type 1.1. Mountain, Hard Rock, Single-Thread Channels with Boulder/Cobble-Dominated Active Channels

Figure 13. Active channel at Caruthers Creek, CA.

Figure 14. Active channel and floodplain at New River, AZ.

Type 1.2. Mountain, Hard Rock, Single-Thread Channels with Sand/Silt-Dominated Active Channels

Figure 15. Active channel at Santa Maria River, AZ.

Figure 16. Active channel at Agua Fria River, AZ.

Section 2. Mountain, Soft Rock Watersheds

Figure 17. Landscape perspective at Santa Cruz Creek, CA.

Figure 18. Landscape perspective at Palm Canyon Wash, CA.

Mountain, Soft Rock, Single-Thread Channels

Table 8. Characteristics of mountain, soft rock, single-thread channels.

Watershed and channel characteristics	Boulder/cobble-dominated active channel	Sand/silt-dominated active channel
Drainage area	50–200 km^2	< 100 km^2
Drainage density	Moderate	Moderate
Drainage shape	Oval–circular	Elliptical–circular
Elevation difference	< 1500 m	< 1500 m
Slope	Shallow–steep	Shallow–steep
Width	< 15 m	< 10 m
Depth	< 3 m	< 1 m
Dominant floodplain texture	Sand and/or silt	Sand
Site locations	Chinle Creek, AZ Dry Beaver Creek, AZ Recapture Creek, UT Rio Puerco, NM Santa Cruz Creek, CA	Moenkopi Wash, AZ Oraibi Wash, AZ Palm Canyon Wash, CA

As with mountain, hard rock watersheds, the dominant texture in the active channel of mountain, soft rock watersheds can be either boulder/cobble or sand/silt (Table 8). Boulder/cobble-dominated channels tend to have larger drainage areas and are slightly wider and deeper than sand/silt channels (W7–W11) (Fig. 8a–d). Boulder/cobble channels display the pool-riffle morphology similar to that in more humid regions; sand/silt channels are more horizontal and planar (W12–W14) (Fig. 8a–d). There is no difference in slope or elevation difference between these two types, and all mountain channels have sand-dominated floodplains.

Type 2.1. Mountain, Soft Rock, Single-Thread Channels with Boulder/Cobble-Dominated Active Channels

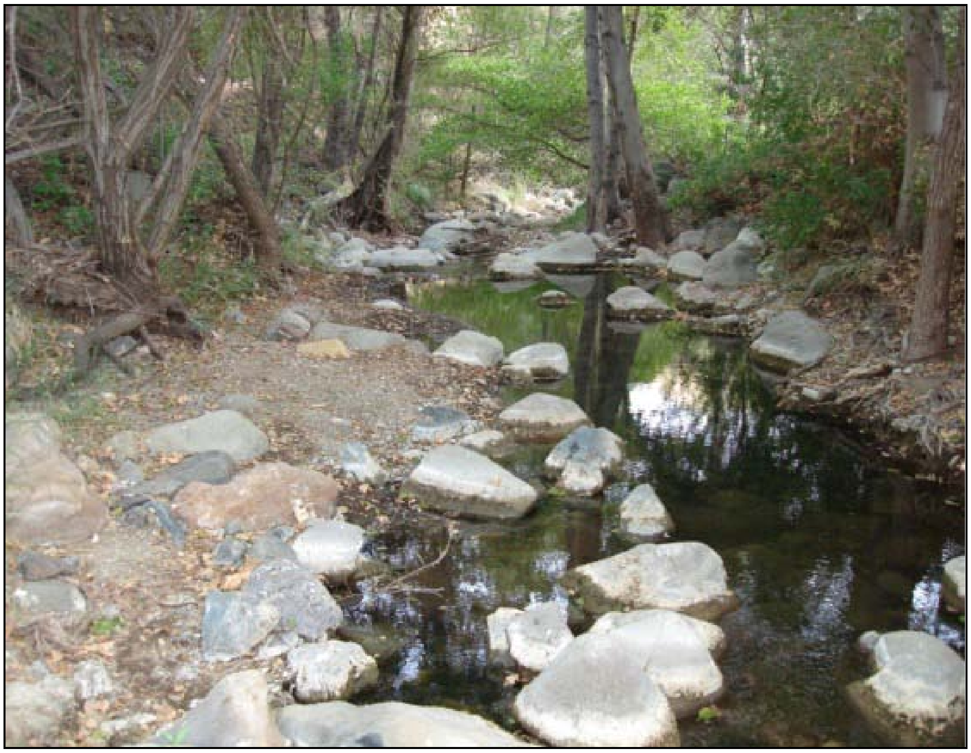

Figure 19. Active channel at Santa Cruz Creek, CA.

Figure 20. Active channel and floodplain at Recapture Creek, UT.

Type 2.2. Mountain, Soft Rock, Single-Thread Channels with Sand/Silt-Dominated Active Channels

Figure 21. Active channel at Oraibi Wash, AZ.

Figure 22. Active channel at Moenkopi Wash, AZ.

4.2 Foothills

In the Arid West foothills, watershed and channel characteristics vary widely. Channel types in this landscape position include single-thread and compound channels in hard rock watersheds and single-thread, compound, and discontinuous ephemeral channels in soft rock watersheds. Compound channels in hard rock watersheds were divided not by texture but by elevation difference because that division showed a difference in watershed and channel characteristics. Below is a list of observations for foothill watersheds in the Arid West region:

- Single-thread channels in hard rock watersheds are dominated by cobbles in the active channel in shallow to moderately sloped watersheds.
- Single-thread channels in soft rock, shallow-sloped watersheds are dominated by either cobble or sand/silt in the active channel.
- Compound channels can be found in watersheds of various slopes and are the most common channel type in hard rock watersheds.
- Hard rock compound channels have wide channels while soft rock compound channels have narrower channels.
- The discontinuous ephemeral channels sampled have shallow slopes and are dominated by sand/silt in the active channel.

Figure 23 shows the foothill channel classification. Figures 24 through 42 are examples of their respective categories.

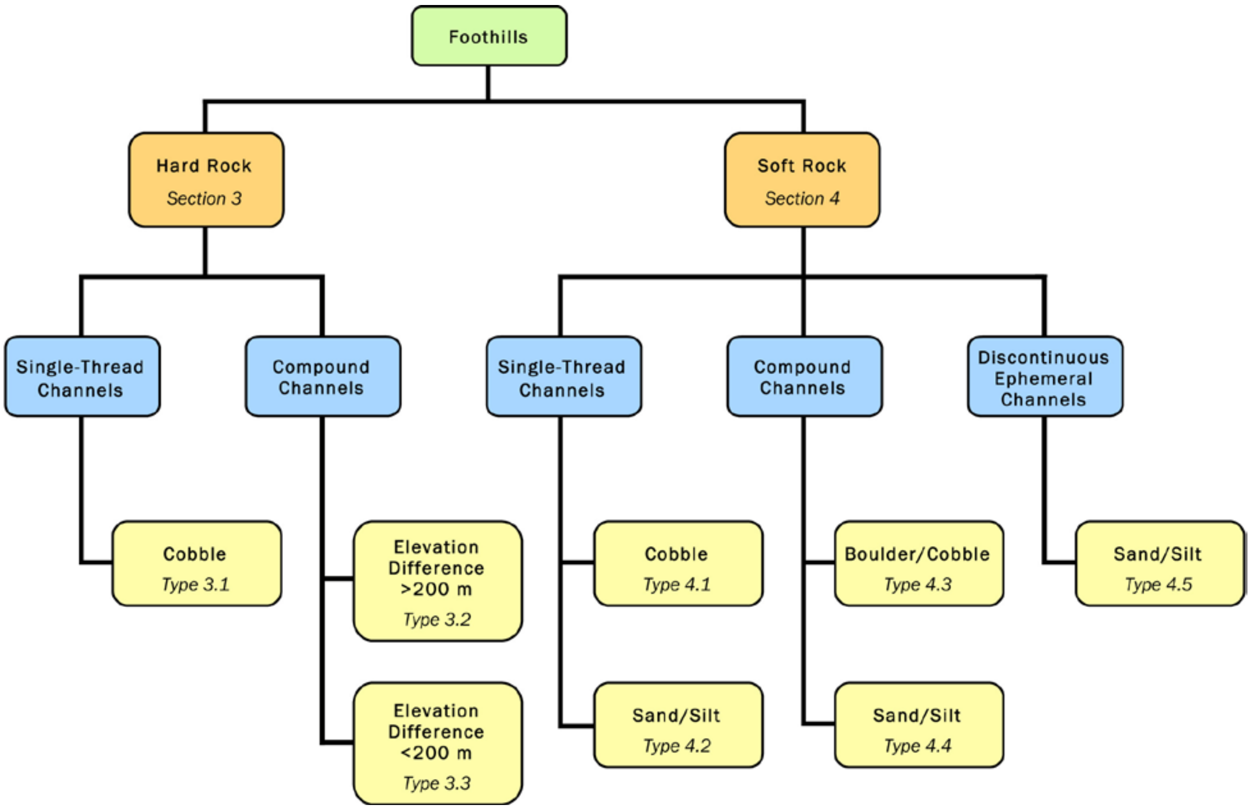

Figure 23. Classification of foothill channels in the Arid West region. In the following descriptions, headings for the orange boxes are bold, blue boxes bold italics, and yellow boxes italics.

Section 3. Foothill, Hard Rock Watersheds

Figure 24. Landscape perspective at Agua Fria River, AZ.

Figure 25. Landscape perspective at Mission Creek, CA.

Foothill, Hard Rock, Single-Thread Channels

Table 9. Characteristics of foothill, hard rock, single-thread channels.

Watershed and channel characteristics	Cobble-dominated active channel
Drainage area	< 100 km^2
Drainage density	Moderate
Drainage shape	Circular
Elevation difference	< 500 m
Slope	Moderate
Width	< 50 m
Depth	< 2 m
Dominant floodplain texture	Sand
Site location	Palm Canyon Wash, CA

Within the foothill, hard rock, single-thread watersheds, we can make no general conclusions about watershed or channel characteristics because of the limited field sites visited that meet the criteria for this watershed type (Table 9). This single-thread channel type is very similar to those found in soft rock watersheds. One of the few differences is that hard rock, single-thread channels have steeper slopes in smaller drainage areas. We extracted the data for this type from only one site (W21) (Fig. 8a–d), and it is likely that there are other channel variations in this group.

Type 3.1. Foothill, Hard Rock, Single-Thread Channels with Cobble-Dominated Active Channels

Figure 26. Active channel at Palm Canyon Wash, CA.

Figure 27. Floodplain at Palm Canyon Wash, CA.

Foothill, Hard Rock, Compound Channels

Table 10. Characteristics of foothill, hard rock, compound channels.

Watershed and channel characteristics	Elevation difference > 200m	Elevation difference < 200m
Drainage area	< 200 km^2	< 200 km^2
Drainage density	Moderate–high	Moderate–high
Drainage shape	Elliptical	Oval–circular
Slope	Shallow–steep	Shallow
Width	< 100 m	< 150 m
Depth	< 3 m	< 4 m
Dominant active channel texture	Cobbles	Cobbles
Dominant floodplain texture	Sand	Sand
Site locations	Mission Creek, CA New River, AZ	Agua Fria River, AZ Rock Creek, NV Santa Maria River, AZ

The defining characteristics differentiating these two hard rock, foothill watershed types are elevation difference along the principal flow path and slope within the watershed (Table 10). There was a distinct difference in channel characteristics when the watersheds are divided this way instead of by texture in the active channel. Channels in this watershed type that have a greater elevation difference within the watershed (W20, W23) also tend to have greater slopes and are narrower and shallower than channels with a lower elevation difference (W15–W17) (Fig. 8a–d). Both types have cobble-dominated active channels, sand-dominated floodplains, and similar drainage areas.

Type 3.2. Foothill, Hard Rock, Compound Channels with Elevation Differences of > 200 m

Figure 28. Active channel and floodplain at Mission Creek, CA.

Figure 29. Active channel at New River, AZ.

Type 3.3. Foothill, Hard Rock, Compound Channels with Elevation Differences of < 200 m

Figure 30. Active channel at Agua Fria River, AZ.

Figure 31. Active channel and floodplain at Santa Maria River, AZ.

Section 4. Foothill, Soft Rock Watersheds

Figure 32. Landscape perspective at Santa Cruz, CA.

Figure 33. Landscape perspective at Moenkopi Wash, AZ.

Foothill, Soft Rock, Single-Thread Channels

Table 11. Characteristics of foothill, soft rock, single-thread channels.

Watershed and channel characteristics	Cobble-dominated active channel	Sand/silt-dominated active channel
Drainage area	< 200 km^2	< 200 km^2
Drainage density	High	Low–moderate
Drainage shape	Oval–circular	Elliptical–circular
Elevation difference	< 200 m	< 500 m
Slope	Shallow	Shallow
Width	< 50 m	< 50 m
Depth	< 2 m	< 2 m
Dominant floodplain texture	Sand	Sand and/or silt
Site locations	McDermitt Creek, NV San Mateo Creek, CA	Moenkopi Wash, AZ Rio Puerco, NM

The dominant texture in the active channel of foothill, soft rock, single-thread channels is either cobble (W24, W25) or sand/silt (W22, W23) (Table 11, Fig. 8a–d). On average, sand/silt channels have a greater elevation difference and a lower drainage density than cobble-dominated channels. Other than those differences, these two types of channels are similar, with comparable drainage areas, widths, and depths and with sand as the dominant floodplain texture.

Type 4.1. Foothill, Soft Rock, Single-Thread Channels with Cobble-Dominated Active Channels

Figure 34. Active channel and floodplain at San Mateo Creek, CA.

Figure 35. Floodplain at McDermitt Creek, NV.

Type 4.2. Foothill, Soft Rock, Single-Thread Channel with Sand/Silt-Dominated Active Channels

Figure 36. Active channel and floodplain at Moenkopi Wash, AZ.

Figure 37. Active channel at Rio Puerco, NM.

Foothill, Soft Rock, Compound Channels

Table 12. Characteristics of foothill, soft rock, compound channels.

Watershed and channel characteristics	Boulder/cobble-dominated active channel	Sand/silt-dominated active channel
Drainage area	< 100 km^2	< 100 km^2
Drainage density	Moderate–high	Moderate
Drainage shape	Oval–circular	Elliptical–circular
Elevation difference	< 1500 m	< 1500 m
Slope	Shallow–steep	Shallow–steep
Width	< 50 m	< 100 m
Depth	< 2 m	< 2 m
Dominant floodplain texture	Sand and/or silt	Sand and/or silt
Site locations	Dry Beaver Creek, AZ Recapture Creek, UT Santa Cruz Creek, CA	Altar Wash, AZ Hassayampa River, AZ

The dominant texture in the active channel of foothill, soft rock, compound channels is either boulder/cobble (W28–W30) or sand/silt (W31, W32) (Table 12, Fig. 8a–d). These channel types tend to be similar, with comparable drainage areas, elevation differences, slopes, and depths of channel and with the floodplain dominated by sand or silt. Boulder/cobble-dominated channels are narrower with a higher drainage density than the sand/silt-dominated channels.

Type 4.3. Foothill, Soft Rock, Compound Channels with Boulder/Cobble-Dominated Active Channels

Figure 38. Active channel and floodplain at Santa Cruz Creek, CA.

Figure 39. Active channel at Dry Beaver Creek, AZ.

Type 4.4. Foothills, Soft Rock, Compound Channels with Sand/Silt-Dominated Active Channels

Figure 40. Active channel at Hassayampa River, AZ.

Figure 41. Active channel and floodplain at Altar Wash, AZ.

Foothill, Soft Rock, Discontinuous Ephemeral Channels

Table 13. Characteristics of foothill, soft rock, discontinuous ephemeral channels.

Watershed and channel characteristics	Sand/silt-dominated active channel
Drainage area	< 200 km^2
Drainage density	Moderate
Drainage shape	Circular
Elevation difference	< 500 m
Slope	Shallow
Width	< 50 m
Depth	< 3 m
Dominant floodplain texture	Sand
Site location	Oraibi Wash, AZ

Within the soft rock foothills, we can make no general conclusions about discontinuous ephemeral channel characteristics because of the limited field sites for this type of channel (Table 13). As with discontinuous ephemeral channels located in basins, they are typically narrow and deeply cut into alluvium. This type also tends to have a shallow slope. Discontinuous ephemeral channel types were seen in the foothills only in soft rock and not in hard rock watersheds. The data within this type were collected from one site (W45) (Fig. 8a–d), and there are likely other channel variations of this group.

Type 4.5. Foothill, Soft Rock, Discontinuous Ephemeral Channels with Sand/Silt-Dominated Active Channels

Figure 42. Active channel at Oraibi Wash, AZ (both views).

4.3 Basins

In the Arid West basins, soft rock watersheds have the greatest variability in channel morphology, with single-thread, compound, and discontinuous ephemeral channels, whereas only compound channels were observed in hard rock watersheds. Below is a list of observations for basin watersheds in the Arid West region:

- All watersheds in soft rock landscapes have shallow slopes.
- Hard rock, compound channel watersheds are divided into types by the dominant texture in the active channel: cobble- or sand/silt-dominated channels. The boulder channels have steep to moderate slopes, while the sand/silt-dominated channels have shallow slopes.
- All hard rock compound channels have wide, shallow channels. Soft rock watersheds generally have narrow, deep channels.
- All channels in basins have sand as the dominant texture in the floodplain.

Figure 43 shows the basin channel classification. Figures 44 through 58 are examples of their respective categories.

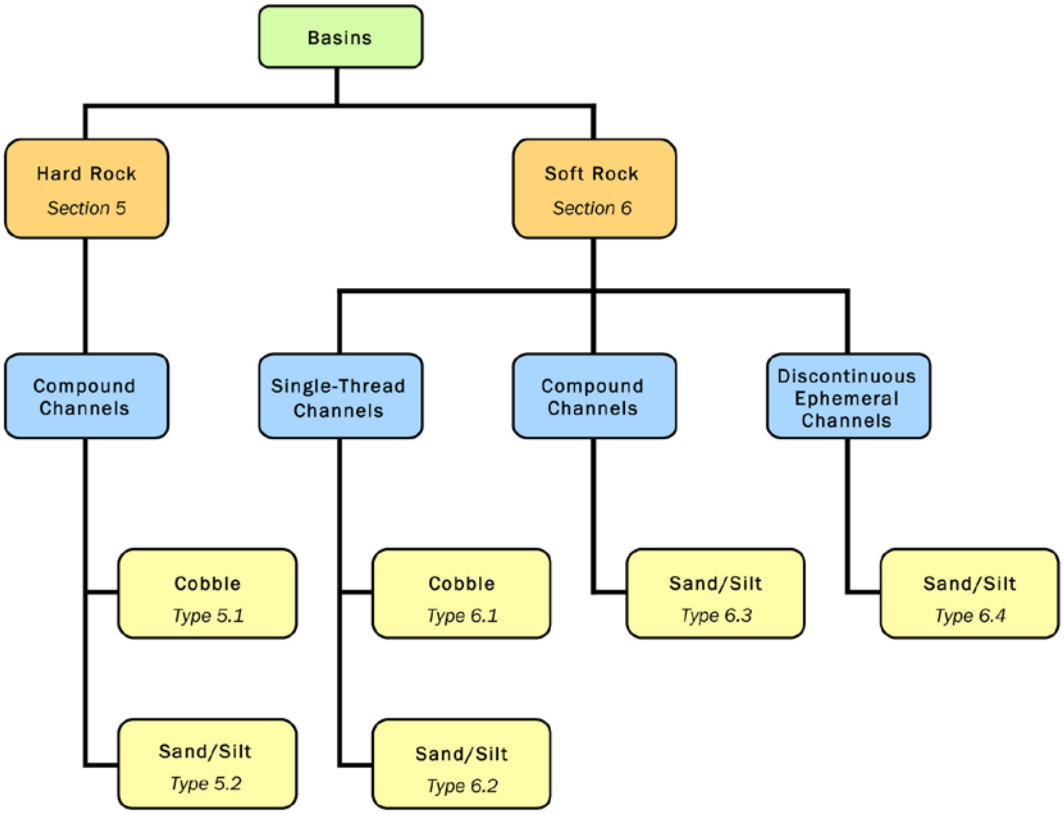

Figure 43. Classification of basin channels in the Arid West region. In the following descriptions, headings for the orange boxes are bold, blue boxes bold italics, and yellow boxes italics.

Section 5. Basin, Hard Rock Watersheds

Figure 44. Landscape perspective at Mojave River, CA.

Figure 45. Landscape perspective at Mission Creek, CA.

Basin, Hard Rock, Compound Channels

Table 14. Characteristics of basin, hard rock, compound channels.

Watershed and channel characteristics	Cobble-dominated active channel	Sand/silt-dominated active channel
Drainage area	< 200 km^2	< 200 km^2
Drainage density	Moderate–high	Moderate
Drainage shape	Elliptical	Oval–circular
Elevation difference	> 500 m	< 500 m
Slope	Moderate–steep	Shallow
Width	< 50 m	< 300 m
Depth	< 2 m	< 2 m
Dominant floodplain texture	Sand	Sand
Site locations	Caruthers Creek, CA Mission Creek, CA	Caruthers Creek, CA Mojave River, CA Palm Canyon Wash, CA Santa Maria River, CA

The dominant texture in the active channel of basin, hard rock, compound channels is cobble (W33, W34) or sand/silt (W35–W38) (Table 14, Fig. 8a–d). Active channels dominated by cobble tend to have greater slopes, elevation differences, and drainage densities. This type has the steepest slopes of any basin channel type. They also tend to be much narrower than the sand/silt-dominated channels because channel widening and braiding within compound channels are more prominent where the sand content in the channel is higher (Lichvar and Wakeley 2004). These channel types have similar drainage areas, sand-dominated floodplains, and depths of less than 2 m. The depth of these channels is one of the key distinctions between hard rock and soft rock compound channels.

Type 5.1. Basin, Hard Rock, Compound Channels with Cobble-Dominated Active Channels

Figure 46. Active channel at Mission Creek, CA.

Figure 47. Active channel at Caruthers Creek, CA.

Type 5.2. Basin, Hard Rock, Compound Channels with Sand/Silt-Dominated Active Channels

Figure 48. Active channel at Santa Maria River, CA.

Figure 49. Active channel at Caruthers Creek, CA.

Section 6. Basin, Soft Rock Watersheds

Figure 50. Landscape perspective at McDermitt Creek, NV.

Figure 51. Landscape perspective at Oraibi Creek, AZ.

Basin, Soft Rock, Single-Thread Channels

Table 15. Characteristics of basin, soft rock, single-thread channels.

Watershed and channel characteristics	Cobble-dominated active channel	Sand/silt-dominated active channel
Drainage area	< 500 km^2	< 200 km^2
Drainage density	Moderate	Low–high
Drainage shape	Elliptical–circular	Oval–circular
Elevation difference	< 500 m	< 200 m
Slope	Shallow	Shallow
Width	< 100 m	< 100 m
Depth	> 1 m	> 1 m
Dominant floodplain texture	Sand	Sand and silt
Site locations	Agua Fria River, AZ McDermitt Creek, NV	Moenkopi Wash, AZ Rio Puerco, NM

The dominant texture in the active channel of basin, soft rock, single-thread channels is either cobble (W46, W47) or sand/silt (W48, W49) (Table 15, Fig. 8a–d). Cobble-dominated channels tend to have slightly greater elevation differences in larger drainages than sand/silt dominated-channels; both have shallow slopes. Both cobble- and sand/silt-dominated channels are incised with widths of less than 100 m.

Type 6.1. Basin, Soft Rock, Single-Thread Channels with Cobble-Dominated Active Channels

Figure 52. Active channel at McDermitt Creek, NV.

Figure 53. Active channel at Agua Fria River, AZ.

Type 6.2. Basin, Soft Rock, Single-Thread Channels with Sand/Silt-Dominated Active Channels

Figure 54. Active channel at Rio Puerco, NM.

Figure 55. Active channel at Moenkopi Wash, AZ.

Basin, Soft Rock, Compound Channels

Table 16. Characteristics of basin, soft rock, compound channels.

Watershed and channel characteristics	Sand/silt-dominated active channel
Drainage area	< 500 km^2
Drainage density	Moderate–high
Drainage shape	Oval–circular
Elevation difference	< 200 m
Slope	Shallow
Width	< 100 m
Depth	> 1 m
Dominant floodplain texture	Sand and/or silt
Site Locations	Altar Wash, AZ Chinle Creek, AZ San Mateo Creek, CA

In basin, soft rock watersheds, compound channels are characterized by only sand/silt in the active channel (W40–W42) (Table 16, Fig. 8a–d). These channels have shallow slopes and are narrower and deeper than basin, hard rock, compound channels. These channels are very similar to basin, soft rock, single-thread channels dominated by cobble, sharing the same frequently occurring OHWM indicators. The primary differences between the two channel types are the channel morphology and the dominant texture within the active channel.

Type 6.3. Basin, Soft Rock, Compound Channels with Sand/Silt-Dominated Active Channels

Figure 56. Active channel at Chinle Creek, AZ (both views).

Basin, Soft Rock, Discontinuous Ephemeral Channels

Table 17. Characteristics of basin, soft rock, discontinuous ephemeral channels.

Watershed and channel characteristics	Sand/silt-dominated active channel
Drainage area	< 500 km^2
Drainage density	Moderate–high
Drainage shape	Elliptical–circular
Elevation difference	< 200 m
Slope	Shallow
Width	< 50 m
Depth	> 2 m
Dominant floodplain texture	Sand and/or silt
Site locations	Oraibi Creek, AZ Susie Creek, NV

Discontinuous ephemeral channels occur more frequently in basin watersheds dominated by soft rock than in any other watershed type in this classification (W43–45) (Table 17, Fig. 8a–d). This type of channel tends to be narrow, deep, and dominated by sand or silt in the active channel. Soft rock, discontinuous ephemeral channels are very similar to soft rock, single-thread channels (except for channel morphology). However, soft rock, discontinuous ephemeral channels tend to be narrower than single-thread channels. Discontinuous ephemeral channels change constantly because of feedback mechanisms (stream velocity, runoff, discharge, etc.) initiated by short-term changes in climate, vegetation, and land use (Bull 1997). More data are necessary to confirm this trend since the number of discontinuous ephemeral channels in this study was small (n = 4).

Type 6.4. Basin, Soft Rock, Discontinuous Ephemeral Channels with Sand/Silt-Dominated Active Channels

Figure 57. Active channel at Oraibi Creek, AZ.

Figure 58. Active channel at Susie Creek, NV.

5 Discussion

We found one pattern to occur frequently across most watersheds in the Arid West region. The majority of watersheds have moderate to high drainage densities, which is compatible with previous studies that suggest that drainage density is typically highest in semi-arid to arid areas (Gordon et al. 2004). There were also no distinct groups or clusters in the PCA ordination that would have suggested significant differences in drainage density in Arid West channels. Watersheds with high drainage densities are associated with flashy, high flood peaks; high sediment production; and erosion of the sparsely vegetated slopes from surface runoff during intense thunderstorms (Dunne and Leopold 1978).

Several channel types are more common in certain landscape settings than in others. Figure 59 shows the percentage of channel types sampled throughout the landscape. The majority of single-thread channels were in the mountains. Single-thread channels located in the foothills and basin typically occur when there is a more continuous supply of water present, such as streams originating in the Western Mountain region, channels that are fed by local springs, and streams that have anthropogenic modifications upstream (Lichvar and McColley 2008). Also, single-thread channels in the Arid West basins and foothills tend to be horizontal and planar (flat and level), and riffle and pool morphology occurs in the mountains and less frequently than in humid climates (Lichvar and Wakeley 2004). The majority of the compound channels sampled were located in the foothills and basins, where they typically form at valley bottoms when channels widen downstream from steep, narrow valleys and canyons (Fig. 8a and 8c) (Montgomery and MacDonald 2002). Compound channels are the most common channel type in the Arid West and are distinguished by single, low-flow channels that are set within a wider, braided channel network. They are subject to widening and avulsions (channel relocation) during moderate- to high-discharge, extreme flow events; during low flows, the low-flow channel is re-established (Lichvar and McColley 2008). Discontinuous ephemeral channels are found in vertical-walled arroyos that are entrenched into a silty valley-floor alluvium where there is an abundant amount of sand, silt, and clay and, therefore, were found more often in basins (Waters and Haynes 2001; Bull 1997).

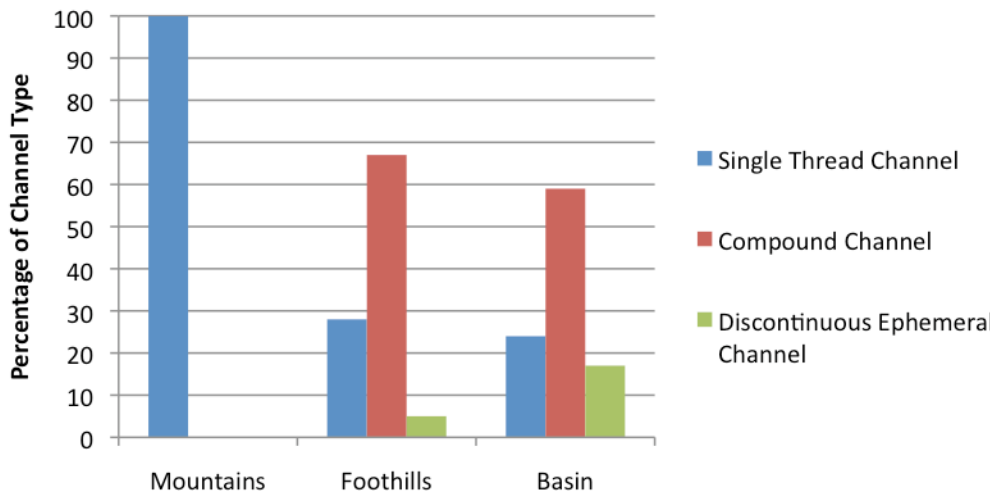

Figure 59. Proportion of channel types visited across the mountain, foothill, and basin landscape positions in the Arid West region.

6 Conclusions

We used multivariate analyses to explore patterns of similarities and differences among the channels in the Arid West region. Although the data show trends with regard to landscape position and active channel sediment type, there are no other discrete groups or clusters upon which we can base an observation-based classification system. Therefore, we proposed an artificial classification based on landscape position for Arid West channels.

This study classified Arid West watersheds into channel types based on general characteristics of watershed and channel morphology (Fig. 9). A total of 18 channel types were classified: 4 were in the mountains, 8 in the foothills, and 6 in the basins. It is important to note that the channel types determined were derived from only the 49 watersheds and channels that were visited and that other types may exist in the Arid West.

Our findings demonstrate that watershed and channel characteristics vary across the landscape in the Arid West. This suggests that channels in the Arid West respond differently depending on the landscape position of the watershed in which they are located. Each channel and watershed is unique and can adjust in a variety of ways to local changes.

This channel classification scheme across the Arid West landscape was not created to explain channel morphology but rather to support OHW delineations and to provide a standard classification system with which to evaluate OHW indicators. Recently, a delineation manual for identifying the OHWM in the Arid West region was published by Lichvar and McColley (2008) with a list of potential OHWM indicators typically found below, at, and above the OHW boundary. The OHW manual indicates a large variability of occurrence of OHW indicators across the channel but did not evaluate the indicators at large scale. To understand the distribution and consistency of OHWM indicators at a larger, watershed scale, OHWM indicators need to be correlated with these channel types to determine if any OHWM indicators or groups of indicators are associated with specific types of channels or landscape positions. The channel types in this classification respond differently to watershed characteristics, and, for delineation purposes, it is important to determine whether OHWM indicators respond in the same manner. The classification scheme described here can, therefore, serve as a useful basis for evaluation of the variability of occurrence of OHW indicators at a larger scale in the Arid West.

References

Bailey, R. G. 1995. *Description of the Ecoregions of the United States*. Miscellaneous Publication 1391. Washington, DC: US Department of Agriculture Forest Service.

Bull, W. B. 1997. Discontinuous ephemeral streams. *Geomorphology* 19:227–276.

Curtis, K., and R. Lichvar. 2010. *Updated datasheet for the identification of the Ordinary High Water Mark (OHWM) in the Arid West region of the western United States*. ERDC/CRREL TN-10-1. Hanover, NH: US Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory.

Curtis, K., R. Lichvar, and L. Dixon. 2011. *Ordinary high flows and the stage-discharge relationship in the Arid West region*. ERDC/CRREL TR-11-12. Hanover, NH: US Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory.

Dana, J. 1850. On denudation in the Pacific. *American Journal of Science, Series 2* 9:48-62.

Davis, W. M. 1899. The geographical cycle. *Geographical Journal* 14:481–504.

Dunne, T., and L. B. Leopold. 1978. *Water in Environmental Planning*. San Francisco, CA: W.H. Freeman.

Field, J. J., and R. W. Lichvar. 2007. *Review and synopsis of natural and human controls on fluvial channel processes in the Arid West*. ERDC/CRREL TR-07-16. Hanover, NH: US Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory.

Gordon, N. D., T. A. McMahon, and B. L. Finlayson. 2004. *Stream Hydrology: An Introduction for Ecologists*. West Sussex, England: John Wiley and Sons.

Graf, W. W. 1988. Definition of flood plains along arid-region rivers. In *Flood Geomorphology*. San Francisco, CA: W. H. Freeman.

Kingsford, R. 2006. *Ecology of Desert Rivers*. United Kingdom: Cambridge University Press.

Kondolf, G. M., D. R. Montgomery, H. Piegay, and L. Schmitt. 2003. Geomorphic classification of rivers and streams. *Tools in Fluvial Geomorphology*. 171–204. Chichester, England: John Wiley and Sons.

Leopold, L. B., and M.G. Wolman. 1957. *River channel patterns—Braided, meandering, and straight*. US Geological Survey Professional Paper 282(B):39–85.

Lichvar, R. W., and J. S. Wakeley, ed. 2004. *Review of Ordinary High Water Mark indicators for delineating arid streams in the southwestern United States*. ERDC/CRREL TR-04-1. Hanover, NH: US Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory. (http://el.erdc.usace.army.mil/elpubs/pdf/tr04-1.pdf).

Lichvar, R. W., and S. M. McColley. 2008. *A field guide to the identification of the Ordinary High Water Mark (OHWM) in the Arid West region of the western United States.* ERDC/CRREL TR-08-12. Hanover, NH: US Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory.

Lichvar, R. W., D. Finnegan, M. Ericsson, and W. Ochs. 2006. *Distribution of Ordinary High Water Mark (OHWM) indicators and their reliability in identifying the limits of "Waters of the United States" in arid southwestern channels.* ERDC/CRREL TR-06-5. Hanover, NH: US Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory. (http://www.crrel.usace.army.mil/techpub/CRREL_Reports/reports/TR06-5.pdf).

Lichvar, R. W., D. Cate, C. Photos, L. Dixon, B. Allen, and J. Byersdorfer. 2009. *Vegetation and channel morphology responses to Ordinary High Water discharge events in Arid West stream channels.* ERDC/CRREL TR-09-5. Hanover, NH: US Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory.

McCune, B. 1988. Ecological diversity in North American pines. *American Journal of Botany* 75:353-368.

McCune, B. and J. B. Grace. 2002. *Analysis of Ecological Communities.* Gleneden Beach, Oregon: MjM Software Design.

McCune, B. and M. J. Mefford. 2006. *PC-ORD: Multivariate Analysis of Ecological Data.* Version 5.14. Gleneden Beach, Oregon: MJM Software.

Montgomery, D. R., and J. M. Buffington. 1997. Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin* 109(5):596–611.

Montgomery, D. R., and L. H. MacDonald. 2002. Diagnostic approach to stream channel assessment and monitoring. *Journal of the American Water Resources Association* 38(5).

Murphey, J. B., L. J. Lane, and M. H. Diskin. 1972. Bed material characteristics and transmission losses in an ephemeral stream. Hydrology and water resources in Arizona and the Southwest. In *Proceedings, 1972 Meeting of the Arizona Section, Arizona Academy Science, Prescott, AZ* 2:455–472.

Nevins, T. H. F. 1965. River classification with particular respect to New Zealand. In *Proceedings of the 4th New Zealand Geography Conference, Dunedin.* New Zealand Geographical Society Conference Series No 4. 83–90.

Palmer, L. 1976. River management criteria for Oregon and Washington. In *Geomorphology and Engineering*, ed. D.R. Coates, 329–346. Stroudsburg, PA: Dowden, Hutchinson, and Ross.

Petit, F. 1995. Regime hydrologique et dynamique fluviale des rivieres ardennaises. In *L'Ardenne, essai de geographie phsique, livre en hommage au Professeur A. Pissart*, ed. A. Demoulin, 194–223. Universite de Liege: Laboratoire d'Hydrographie et de Geomorphologie Fluviatile.

Powell, J. W. 1875. *Exploration of the Colorado River of the West and its tributaries.* Washington, DC: US Government Printing Office.

Reid, I., and L. E. Frostick. 1997. Channel form, flows and sediments in deserts. In *Arid Zone Geomorphology: Process, Form and Change in Drylands.* 205–229. Chichester, NY: John Wiley.

Rosgen, D. 1996. *Applied River Morphology.* Pagosa Springs, CO: Wildland Hydrology.

Schumm, S. A. 1961. *Effect of sediment characteristics on erioson and deposition in ephemeral-stream channels.* Professional Paper 352-C. Reston, VA: US Geological Survey.

SYSTAT Software, Inc. 2007. San Jose, CA.

Strahler, A. N. 1957. Quanitative analysis of watershed geomorphology. *Transactions, American Geophysical Union* 38(6):913–920.

Tooth, S. 2000. Process form and change in dryland rivers: A review of recent research. *Earth-Science Review* 51:67–107.

US Department of Agriculture. 2007. *Rapid watershed assessments. Watersheds, Hydrologic Units, Hydrologic Unit Codes, Watershed Approach, and Rapid Watershed Assessments.* (http://www.nrcs.usda.gov/programs/rwa/Watershed_HU_HUC_WatershedApproach_defined_6-18-07.pdf)

US Department of Agriculture. 2010. *Geospatial data gateway.* (http://datagateway.nrcs.usda.gov/).

US Geological Survey. 2006. *National atlas of the United States. Generalized geologic map of the United States, Puerto Rico, and the US Virgin Islands.* (http://pubs.usgs.gov/atlas/geologic/).

US Geological Survey. 2010. *National hydrography dataset.* (http://nhd.usgs.gov/).

Waters, M. R., and C. V. Haynes. 2001. Late Quaternary arroyo formation and climate change in the American Southwest. *Geology* 29:399–402.

Wohl, E., and H. Achyuthan. 2002. Substrate influences on incised-channel morphology. *Journal of Geology* 110:115–120.

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14. ABSTRACT

The Arid West region is dominated by watersheds that have a high frequency of intermittent and ephemeral channels. These channels are influenced by watershed characteristics and the local hydrologic regime, which dictate the amount of sediment deposited and eroded in the channel. Over time, this sediment movement causes the geometry of the channel and the surrounding floodplain to evolve. For this study, 14 mountain, 18 foothill, and 17 basin ephemeral and intermittent channels within multiple watersheds were evaluated for specific characteristics, including geology, slope, watershed design, and floodplain geomorphology. We used multivariate analyses to explore patterns of similarities and differences among the channel and watershed characteristics. Using these results and characteristics, a simple, artificial channel classification to evaluate OHW indicators was devised to better understand watershed and intermittent and ephemeral channels across the landscape in the Arid West region. A total of 18 channel types were classified: 4 in the mountains, 8 in the foothills, and 6 in the basins. Our findings demonstrate that watershed and channel characteristics vary considerably across the landscape in the Arid West, suggesting that channel classification is potentially useful for evaluating the variability of occurrence of OHW indicators at a larger scale.

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