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A geomorphic classification of ephemeral channels in a mountainous, arid region, southwestern Arizona, USA

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ABSTRACT

Despite the global abundance of arid-region ephemeral streams, hydrologic and geomorphic data for these systems are limited compared to their perennial counterparts. High spatial and temporal variability in flow makes hydrologic and geomorphic aspects of dryland ephemeral channels difficult to characterize. Perennial stream classifications have been extended to dryland ephemeral streams but do not adequately describe observed differences in channel geometry and characteristics of ephemeral channels in desert environments. We present a geomorphic classification for ephemeral streams in mountainous regions based on planform, degree of confinement, and composition of confining material. Five stream types were identified in the Sonoran desert of southwestern Arizona: (1) piedmont headwater, (2) bedrock, (3) bedrock with alluvium, (4) incised alluvium, and (5) braided channels. Nonparametric permutational multivariate analysis of variance for 101 surveyed reaches indicated differences ($p < 0.001$) in channel geometry and hydraulics among the five stream types. Nonmetric multidimensional scaling ordination identified the strongest channel geometry and hydraulic variables capable of distinguishing the five channel types, and a classification tree determined relative importance of these variables in the following order: width-to-depth ratio (W/D), stream gradient (S), stream power (Ω), and shear stress (τ). A classification tree and discriminant analysis used W/D, S, Ω, and τ for 86 study reaches on the U.S. Army Yuma Proving Ground (77% and 77% internal validation hit rate, respectively) to predict stream type of 15 separate study reaches on Barry Goldwater Air Force Range with 67% and 73% external validation hit rates, respectively. Differences in channel geometry among the five stream types reflect likely differences in hydrology, hydraulics, and sediment transport with implications for disturbance regime, channel adjustment to disturbance, and ecological sensitivity.

1. Introduction

Understanding the relationships between physical and biological characteristics of fluvial ecosystems is crucial to assessing their sensitivity to natural and anthropogenic disturbances. Our knowledge of hydrologic, geomorphic, and ecological relationships in dryland ephemeral channels, however, is hindered by limited data sets. In addition, classifications created for perennial streams are commonly used for intermittent and ephemeral streams, even though the classifications do not adequately address the geomorphic characteristics of channel networks in arid regions.

In this paper, we developed and test an *a priori* channel classification based on the physical characteristics of ephemeral channels in a mountainous desert region. The classification focuses on channel geometry, as reflected in differences among channel planform, lateral confinement, and composition of boundary materials. We emphasize these characteristics because they persist for tens to hundreds of years and are readily identified in the field. Channel geometry also strongly influences the distribution of hydraulic forces and the transport of sediment and nutrients (Hassan, 1990; Powell et al., 1998). A classification based on channel geometry can provide insights into the processes occurring during infrequent and episodic flows, which are typically of short duration and difficult to observe or measure. This classification provides a foundation for investigating the relationships between channel geometry and geomorphic processes.

1.1. Ephemeral streams in arid regions

Ephemeral streams constitute a significant portion of river networks in arid regions, which cover approximately one-third of Earth's land surface (Cooke and Warren, 1973). Spatial and temporal relationships of fluvial processes vary greatly between dryland rivers and those in humid regions (Graf, 1988a; Reid and Laronne, 1995; Tooth, 2000; Bull and Kirkby, 2002; Reid and Frostick, 2011). Recurrence intervals for bankfull flows in arid-zone rivers range from ~1 to 32 years, as

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opposed to ~1.5-year recurrence intervals typical of temperate zone rivers (Graf, 1988a; Bull and Kirkby, 2002). Infrequent, sporadic, and segmented flows in arid regions reflect spatial variability in precipitation significant enough to produce runoff, and the discontinuity of flow conveyance.

Ephemeral streams typically exhibit large downstream decreases in unit discharge (Babcock and Cushing, 1941; Cornish, 1961; Lane et al., 1971; Walters, 1989; Hughes and Sami, 1992; Goodrich et al., 1997) as a result of storms covering only a portion of a watershed. In addition, substantial transmission losses result from high rates of evapotranspiration and infiltration into dry, unconsolidated alluvial beds, creating a positive feedback (Keppel and Renard, 1962; Constantz et al., 1994; Bull, 1997; Goodrich et al., 1997; Tooth, 2000). Infiltration losses decrease flow depth and sediment transport capacity, cause aggradation in low-gradient channel segments, and increase the volume of stored alluvium. Enhanced sediment deposition within channels maintains high infiltration rates and subsurface storage capacity, increasing the potential for further transmission losses (Graf, 1988a; McDonald et al., 2004; Reid and Frostick, 2011). Downstream increases in the extent and thickness of alluvium, and associated transmission losses, can lead to increased subsurface moisture storage in ephemeral channels, supporting more abundant and functionally diverse vegetation (Shaw and Cooper, 2008).

Decreased transport capacity associated with transmission losses and flow obstruction by vegetation creates a positive feedback for instream aggradation (Graf, 1988a; Merritt and Wohl, 2003; Reid and Frostick, 2011). Aggradation increases storage capacity of subsurface water and promotes vegetation establishment and increased flow resistance (Bull, 1977; Graf, 1981, 1988a; Stanley et al., 1997; Knighton, 1998; Tooth, 2000; Tooth and Nanson, 2000; Comporeale et al., 2006; Reid and Frostick, 2011). Woody vegetation can limit channel adjustment during subsequent flows by enhancing the erosional resistance of banks and bars (Merritt and Wohl, 2003; Perucca et al., 2007; Camporeale et al., 2013).

Perennial streams with coarse-grained sediment are reportedly more ecologically productive than those composed of finer silt- and clay- sized particles (Allan, 1995; Waters, 1995), but the accumulation of silt in dryland channels may facilitate storage of water in micropores on annual time scales (Brooks et al., 2009). The filling of pore spaces with fine sediment on alluvial streambeds following transmission losses (Knighton, 1998; Bull and Kirkby, 2002; Reid and Frostick, 2011) can result in complex layering that limits downward flow (Graf, 1981; Ronan et al., 1998) and results in water retention closer to the surface.

In contrast to alluvial washes, adjacent upland surfaces in arid regions are commonly characterized by desert pavement underlain by a relatively impermeable silty, clay-rich A_z vesicular horizon (McFadden et al., 1987, 1998). These surfaces limit infiltration capacity, increase overland flow, and contribute to the flashy runoff response of ephemeral channels (Graf, 1988a; McAuliffe, 1994; Tooth, 2000; Bevens, 2002; Bull and Kirkby, 2002; Young et al., 2004; Wood et al., 2005). Surface runoff and channel patterns on upland piedmont surfaces reflect past depositional environments or inherited memories (*sensu* Sidorchuk, 2003) by concentrating flow and facilitating channel initiation in topographic depressions.

Complex response to short-lived infrequent flows in arid-region ephemeral streams results in progressive episodes of cutting and filling (Schumm, 1977; Patton and Schumm, 1981) accompanied by channel widening (Hooke, 1967; Bull, 1997; Powell et al., 2005). Progressive aggradation in braided channels commonly results in the development of secondary channels perched above the main channel (Keppel and Renard, 1962; Graf, 1988a; Reid and Frostick, 2011). During periods of relatively more frequent and lower magnitude flows, braided channels typically develop compound meandering channels inset across the braided valley bottom (Graf, 1988b). Infrequent, high-magnitude floods can completely restructure ephemeral channel geometry and temporary flow characteristics in arid regions (Graf, 1988a), but ephemeral streams tend to maintain similar flow characteristics over longer periods of time (Bull and Kirkby, 2002).

Despite the relative long-term stability of flow characteristics in ephemeral streams, channel characteristics commonly exhibit spatial variability and longitudinal discontinuity in arid regions. Longitudinal changes in channel planform commonly occur with changes in lithology and valley characteristics. For example, single-thread channels can transition into braided as valleys widen (Leopold et al., 1964; Graf, 1981; Bull, 1997). This adjustment in planform is accompanied by decreased flow depth and velocity, abrupt decreases in channel gradient, increased infiltration losses, declining unit discharge, and abundant sediment input resulting in part from bank erosion (Graf, 1988a; Knighton, 1998; Bull and Kirkby, 2002; Reid and Frostick, 2011).

2. Regional setting

Study sites included ephemeral watersheds ranging in size from 0.0014 to 23,000 ha within the U.S. Army Yuma Proving Ground (YPG; >3300 km^2) and Barry M. Goldwater Air Force Range (BMGR; >6800 km^2) in southwestern Arizona within the Sonoran desert (Fig. 1). The primary study area and source of the calibration data set for the stream classification were the western portion of YPG within watersheds ranging in elevation from 90 to 860 m. Data used for verification and testing of the classification system were collected and derived from the eastern side of BMGR in watersheds of 260 to 1250 m elevation.

The YPG and BMGR lie within the Basin and Range physiographic province, where broad alluvial lowlands separate individual mountain ranges. Heterogeneous soil characteristics on various surfaces result in highly variable infiltration rates (Bacon et al., 2008). The most common surface types within the study areas are (i) exposed intrusive and extrusive igneous bedrock of primarily felsic composition (Eberly and Stanley, 1978), (ii) unconsolidated alluvial sediments in washes with relatively frequent hydrologic and anthropogenic disturbances, and (iii) desert pavement on relict alluvial fan and piedmont surfaces (McDonald et al., 2009). The YPG and BMGR are used for various military training activities and contain limited public access roads.

Convective summer storms and dissipating tropical cyclones create temporally and spatially variable warm-season precipitation in the

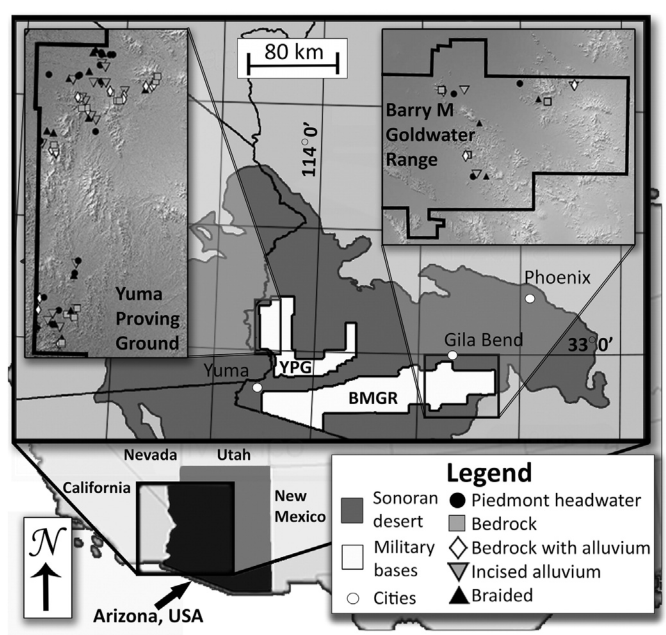

Fig. 1. Locations of 101 study reaches within the U.S. Army Yuma Proving Ground (YPG) and Barry Goldwater Air Force Range (BMGR) in southern Arizona within the extent of the U.S. Sonoran desert, as defined by Brown et al. (2007).

Sonoran desert, while Pacific frontal storms generate widespread, low-intensity rainfall during winter months. A distinct dry season occurs from April to June, and a wet season occurs from November to March; but approximately half of annual precipitation in the research area falls during the period from July to September (National Weather Service, 2012; Western Regional Climate Center, 2012a,b). Total average annual rainfall at YPG is 95 mm, whereas total average annual rainfall in Gila Bend (~30 km north of BMGR) is 156 mm (Western Regional Climate Center, 2012a,b). Abundant vegetation and dense stands of trees are restricted to riparian areas. Common woody xeroriparian vegetation includes ironwood (*Olneya tesota*), palo verde (*Parkinsonia florida* and *P. microphylla*), acacia (*Acacia* spp.), mesquite (*Prosopis* spp.), white bursage (*Ambrosia dumosa*), and creosote (*Larrea tridentata*). Uplands are dominated by creosote bush and white bursage.

3. Materials and methods

3.1. Proposed ephemeral stream classification

Existing geomorphic classifications refer primarily to characteristics of perennial streams and do not adequately describe relevant, reach-scale, geomorphic characteristics of ephemeral channels. Bankfull stage and width provide examples of concepts that are important in classifications developed for perennial streams but are difficult to apply to ephemeral channels. Bankfull stage in perennial channels is typically associated with a channel-forming flow that occupies the entire channel on average every 1.5 years (Leopold et al., 1964; Dunne and Leopold, 1978; Knighton, 1998) and transports the majority of suspended sediment (Simon et al., 2004). Ephemeral streams may experience aggradation for decades without significant channel-altering flows (Graf, 1981) and undergo substantial erosion during large floods (Graf, 1988a; Kondolf et al., 2001; Friedman and Lee, 2002; Merritt and Wohl, 2003). This makes it difficult to identify a single flow magnitude, or associated channel width or flow stage, that adequately represents channel adjustment over a period of decades (Graf, 1988b; Tooth, 2000). Lack of information on flow magnitude and recurrence intervals for ephemeral streams is exacerbated by the paucity of flow data in arid environments.

Our ephemeral channel classification is based on channel planform, the degree of lateral confinement and composition of confining material. These criteria represent relatively persistent features, unlike alluvial bedforms that can change substantially during a single flood. Planform, lateral confinement and channel boundary composition influence hydraulics and sediment dynamics (Hassan, 1990; Powell et al., 1998), which are difficult to measure in ephemeral channels (Bull and Kirkby, 2002). Channel geometry, hydraulics, and sediment dynamics influence riparian structure and function via habitat creation and destruction (Birkeland, 1996; Hupp and Osterkamp, 1996; Merritt and Wohl, 2003). The classification presented here focuses on persistent aspects of channel geometry that can be used as indicators of transient channel processes, just as the Montgomery and Buffington (1997) channel classification for mountainous perennial channels focuses on persistent bedforms as indicators of relative sediment supply and mobility. The channel types proposed here could be applied to rivers in diverse environments, but they are particularly suitable for arid-region ephemeral channels in mountainous areas.

Our classification draws on existing classifications that describe planform (Leopold et al., 1964), longitudinal zonation within drainage basins (Schumm, 1977; Bull, 1979), and process domains (Montgomery, 1999; Polvi et al., 2011). As channel slope decreases from mountainous uplands toward broad lowland valleys, progressively higher order streams exhibit decreases in stream power (Bull, 1979). This creates an idealized spectrum where upland channels are confined primarily by bedrock along the bed and banks, which transition into alluvial bed channels confined by bedrock. As distance from the mountainous uplands increases, these channels incise through previously deposited sediment and alluvial fans, which compose the piedmont. We initially developed an *a priori* classification of five channel types distinguished based on simple visual characteristics. The goal of this paper is to objectively test whether differences in channel geometry and hydraulic parameters existed between our channel types.

Our *a priori* classification included five channel types. *Piedmont headwater* channels initiate on piedmont surfaces and are incised into partially consolidated alluvium, yet lack persistent active alluvium on the channel bed and do not exhibit significant point bar or floodplain development (Fig. 2A). Montane *bedrock* channels are entirely confined by exposed bedrock and devoid of persistent alluvium (Fig. 2B). *Bedrock with alluvium* channels are confined by bedrock, but contain a persistent bed of active alluvium for at least 50% of the study reach length, and may exhibit point bars and narrow floodplain benches (Fig. 2C). *Incised alluvium* channels contain active alluvial beds that are bound only by the partially consolidated alluvium composing the piedmont into which they are incised (Fig. 2D). These channels may exhibit significant floodplain and point bar development, or have narrow floodplain benches. Depositional *braided* washes exhibit multiple channels and transient gravel bars, regardless of the degree and composition of confining material (Fig. 2E). Primary qualitative differences between channel types are those pertaining to valley confinement. The relative degrees of valley confinement are captured in typical cross sections of each proposed channel type, where multiple channels and relatively well-developed floodplains are evident in braided and incised alluvial reaches, respectively (Figs. 3, 4).

The five channel types thus represent an idealized downstream progression from eroding channel segments that initiate on the piedmont (A) or in the mountains (B), downstream channel segments on the piedmont that have larger drainage area, numerous tributaries and at least some depositional features and potential for subsurface water storage (C and D), and larger channels in the alluvial basins between mountain ranges that have extensive deposition and greater potential for subsurface water storage (E; Fig. 2). Channel characteristics reflect many aspects of the climate and landscape including antecedent features and accommodation space as described by Fryirs and Brierley (2010), which are a function of the lithotopographic footprint (Montgomery, 1999; Beechie et al., 2010) and geomorphic memory (Sidorchuk, 2003) from past processes. Reach-scale channel characteristics and spatial transitions between channel types are dependent upon discontinuity of upland geomorphic surfaces, exposure and lithology of bedrock, and location of tributary junctions. This heterogeneity of the landscape controls process domains – analogous to those described by Montgomery (1999) for humid temperate environments – and associated channel characteristics in locations where channel dimensions can be strongly influenced by debris flow, sheet flow, confined channelized flow, or minimal confinement. We emphasize that the longitudinal progression mentioned above is idealized in the sense that it represents very broad-scale patterns. An individual channel could change downstream from bedrock to incised alluvium to bedrock with alluvium and then braided, for example, as a function of downstream variations in surface bedrock exposure.

3.2. Objectives and hypothesis

The objective of this paper is to identify the characteristics of measured channel geometry and inferred hydraulics among five *a priori* proposed ephemeral channel types. We address this by (i) testing the hypothesis that the five proposed stream types exhibit significantly different channel geometry and reach-scale hydraulics, (ii) determining ranges of values in reach-scale hydraulics and channel geometry for each channel type in this study area, and (iii) testing the validity of such a classification by predicting channel types for an external validation data set using discriminant analysis and a classification tree.

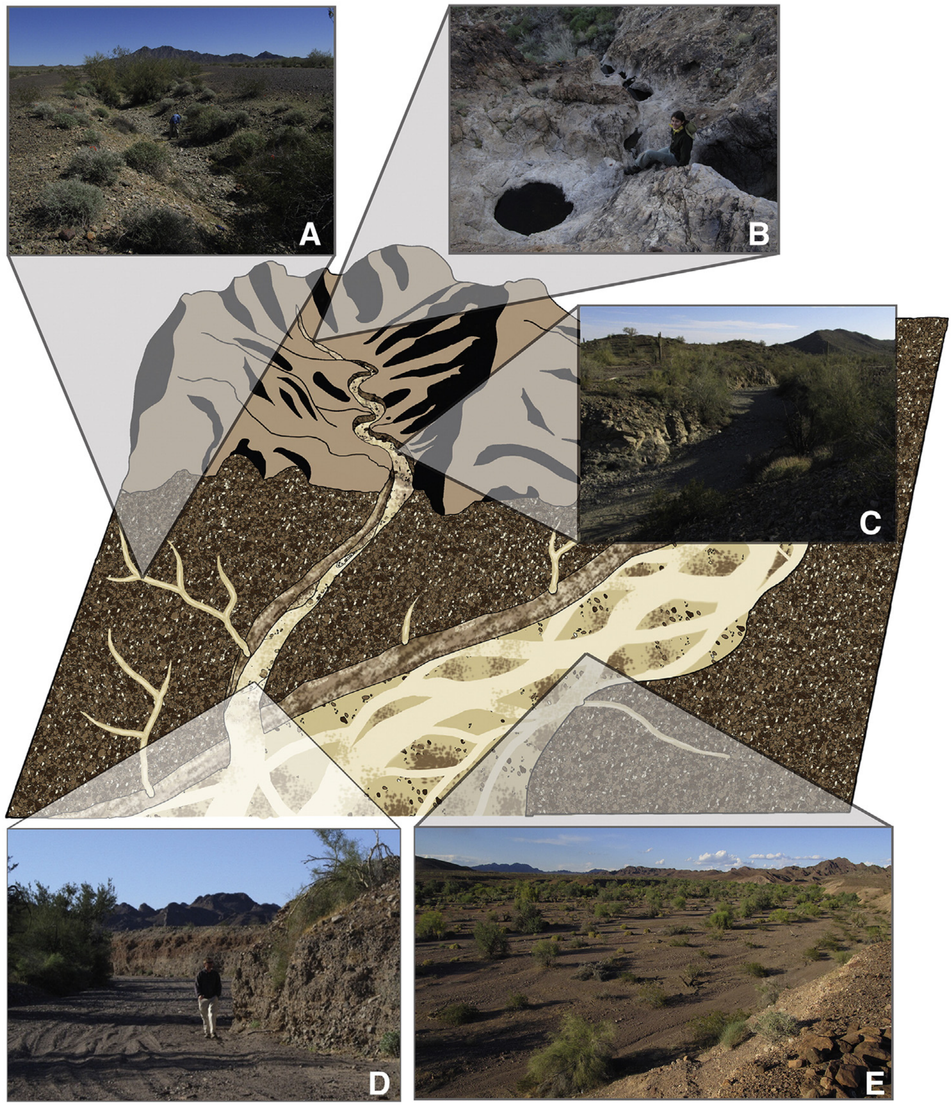

Fig. 2. Five arid-region ephemeral channel types depicted as an idealized progression include primarily erosive piedmont headwater (A) and bedrock (B) channels, those located in intermediate transfer zones along the transition from the mountain front to the piedmont or adjacent to the piedmont (bedrock with alluvium (C) and incised alluvium (D)) and primarily depositional braided channels (E).

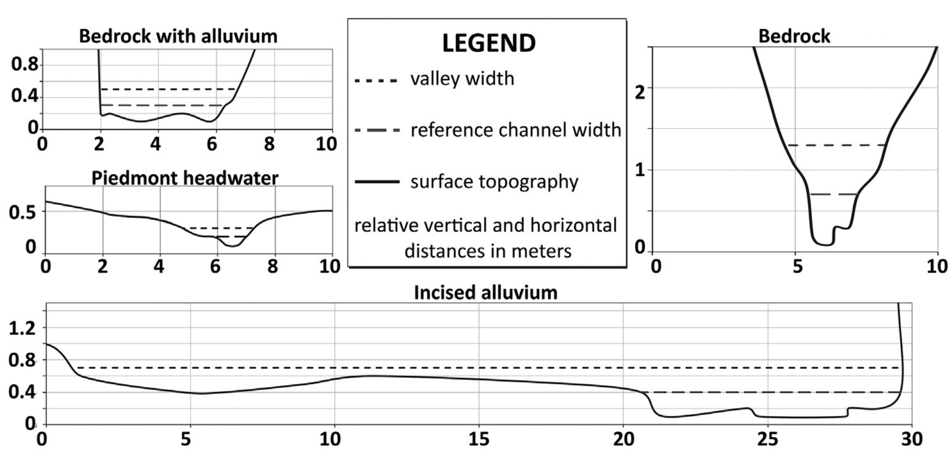

Fig. 3. Representative cross-sectional profiles for bedrock, bedrock with alluvium, piedmont headwater, and incised alluvium channel types. Figures are in relative scale to one another with vertical and horizontal axes in meters. Refer to Fig. 3 for a typical cross section of a braided wash at a significantly different scale.

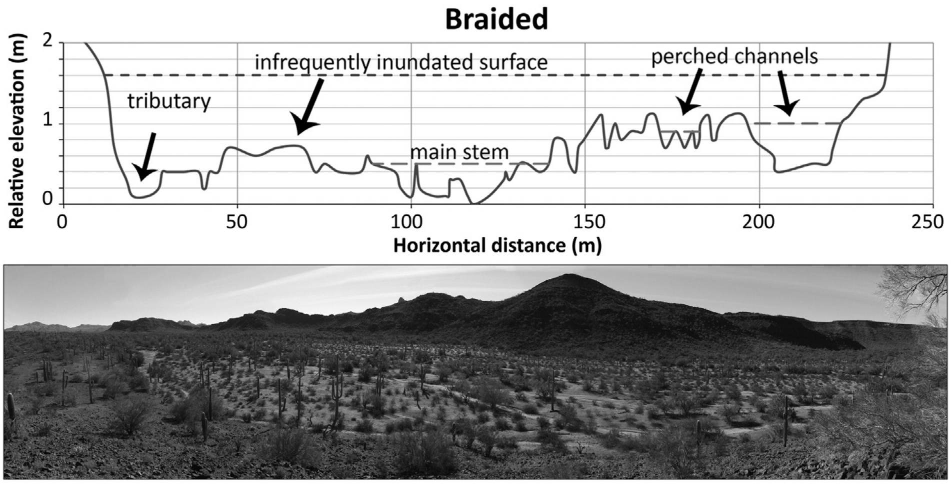

Fig. 4. Braided wash cross-sectional profile from Yuma Proving Ground illustrating typical features of a braided channel. The ratio between valley width (upper short-dashed line) to channel width (lower long-dashed lines) (W_v/W_c) is calculated by the valley width (at an elevation approximately two times the maximum depth of the highest channel within the braided wash) over the sum of channel widths. The photograph depicts the view of a braided wash in Barry M. Goldwater Range from valley right.

3.3. Reach surveys

Stratified sampling and field visits were used to select study reaches that were representative of each channel type. We attempted to select study sites that encompassed the full range of variability in physical characteristics of each channel type (e.g., scale, stream gradient, lithology, width/depth ratio) observed in the field, but avoided study reaches that exhibited evidence of possible transitional states between stream types. Study reaches were located to avoid confounding effects of tributary junctions and intensive anthropogenic disturbance.

Channel geometry and reach characteristics for 101 study reaches at YPG and BMGR were surveyed using a Laser Technology TruPulse 360B laser rangefinder with 10-cm accuracy. Data collection at 86 study reaches in YPG consisted of channel surveys for 19 piedmont headwater (PH), 18 bedrock (BK), 18 bedrock with alluvium (BA), 18 incised alluvium (IA), and 13 braided (BD) study reaches. Sufficiently long braided study reaches were difficult to find that did not have large tributary confluences or changes in channel characteristics. Downstream changes in channel characteristics, for example, included the loss of a well-defined channel resulting from transmission losses. This smaller sample size for BD reaches, however, reflects the lower abundance of this stream type in the study area. Reach surveys conducted at BMGR included three study reaches representing each of the five channel types, totaling 15 study reaches in the external validation data set.

Cross sections were surveyed with respect to a reference stage, which we assume represents the discharge responsible for maintaining contemporary channel geometry. We make no attempt to define specific discharges for channel-forming flows and avoid the use of bankfull stage because it has become associated with recurrence interval in perennial streams (Leopold et al., 1964; Knighton, 1998; Benda et al., 2005). We refer instead to a reference stage using topographic features in a way that is analogous to bankfull stage, defined as the change in slope of the stage-discharge rating curve (Williams, 1978). We delineated reference stage based on development of desert varnish and desert pavement on adjacent upland surfaces as an upper limit, height of fluvial depositional surfaces as a lower limit, and staining on bedrock within the channel. The reference flow stages identified in the field may not represent the large floods responsible for scouring and shaping the channel prior to numerous depositional events. However, this stage likely represents the most common (median) flow depth under modern climate responsible for creating and maintaining current channel geometry. In this respect, reference flows likely represent the hydrologic and geomorphic conditions responsible for maintaining contemporary riparian vegetation community structure rather than specific events with distinct magnitudes or recurrence intervals.

Four cross sections were spaced approximately four mean channel widths apart, with the exception of braided washes where cross sections were spaced by one width of the entire fluvial corridor (wash width). Cross-sectional profiles based on identification of reference flows provide information about channel geometry for estimates of width-to-depth ratio, ratio of valley-to-channel width, shear stress, dimensionless shear stress, stream power, and unit stream power.

Length of each study reach was defined as 3 wash widths for braided channels and 12 mean channel widths for all other reach types. Longitudinal streambed profiles for all reach types except braided reaches were surveyed at consecutive points along the best approximation of the thalweg for a distance of at least one channel-width beyond the upstream- and downstream most cross sections. Topographic elevation was surveyed at slope breaks, changes in grain size, and bends in the channel. The GIS-derived slopes were preferred for stream gradient calculations in BD reaches because of the large scale of braided valley bottoms and difficulty in achieving accurate thalweg slope estimates. Longitudinal profiles for BD reaches were calculated using 5-m digital terrain models (DTM) (McDonald and Hernandez, 2011) for YPG and 10-m digital elevation models (DEM) (Arizona Land Resource Information System, 2012) for BMGR.

Streambed surface pebble counts of at least 100 clasts were made at every study reach with the exception of bedrock channels devoid of alluvium. Sample intervals were scaled according to channel width. Using a modified Wentworth scale, each pebble was classified by the length of the median axis into one of eight grain size categories ranging from sand (i.e., 0.33 to 2 mm) to boulders (i.e., >128 mm; Wentworth, 1922).

3.4. Reach-scale channel hydraulics

Reach-scale estimates of channel geometry and hydraulic parameters were derived by averaging values across the four surveyed cross sections within each reach. Flow depth was based on reference stage. Average velocity (V) and discharge (Q) were calculated using the Manning equation (Knighton, 1998) for each study reach,

$$V = (k/n)R^{2/3}S^{1/2} \quad (1)$$

where $k = 1$ in SI units, R is the hydraulic radius, S is stream gradient estimated as slope of the channel bed, and n is the roughness coefficient.

Estimates of Manning's roughness coefficient (n) were initially derived using an adapted version of the Cowan method (Arcement and Schneider, 1989), yielding estimated n values within the range of 0.03 to 0.06. Because visual estimation of roughness values is subjective, survey accuracy is limited, and the Manning equation assumes steady, uniform flow, we considered all estimates of hydraulic variables to be first-order approximations. Discharge (Q) was estimated as the product of V and A. Discharge estimates were used to calculate stream power (Ω) and unit stream power (ω) as a proxy for hydraulic driving forces:

$$\Omega = \gamma QS \tag{2}$$

$$\omega = (\gamma QS)/w = \Omega/w \tag{3}$$

where γ is the specific weight of water. In order to focus our analyses on measured variation in channel morphology and to standardize uncertainties in estimating roughness coefficients, our first-order approximations of Ω and ω used the lowest estimate of Manning's roughness coefficient for all study reaches ($n = 0.03$) to examine relative differences between channel types. Shear stress was calculated using

$$\tau = \gamma RS \tag{4}$$

To incorporate median grain size (d_{50}) in the analysis of hydraulics, dimensionless shear stress was calculated using

$$\tau^* = (RS)/(1.65d_{50}) \tag{5}$$

The ratio W_v/W_c was calculated for all stream types using entrenchment ratio and the reference flow width and depth (Rosgen, 1994). Entrenchment ratio is the floodprone width (width of the channel/valley at two times the bankfull depth) over the bankfull width (Rosgen, 1994). Floodprone width was measured for braided reaches at two times the maximum depth of the channel highest in elevation along the valley bottom.

3.5. Statistical analyses

Eight metrics (stream gradient S, width/depth ratio W/D, ratio of valley width to channel width W_v/W_c, shear stress τ, dimensionless shear stress τ^*, median grain size d_{50}, stream power Ω, and unit stream power ω) were calculated and examined for strength as predictor variables in multivariate analyses. A combination of univariate and multivariate statistical methods were used to (i) examine the strength of variables in distinguishing channel types, (ii) test the hypothesis that the five channel types exhibit significantly different values of channel geometry and inferred hydraulics, (iii) examine potential range of values for variables of interest between channel types, and (iv) validate the basis of the channel classification by predicting channel type using indicator variables. These statistical methods include one-way analysis of variance (ANOVA) with multiple contrasts and comparisons, nonparametric permutational multivariate analysis of variance (PerMANOVA) (Anderson, 2001), nonmetric multidimensional scaling (NMS) (Clarke, 1993), classification trees (Breiman et al., 1984; De'ath and Fabricius, 2000), and linear discriminant analysis (LDA).

Variables were $\log_{10}$ transformed to achieve approximate normality and homoscedasticity that satisfied the assumptions of our statistical analyses. Individual one-way analysis of variance (ANOVA) and multiple comparisons and contrasts were conducted between channel-type group means for each of the eight variables (ω, τ, W/D, S, Ω, W_v/W_c, τ^*, d_{50}) to determine potential strength of variables for distinguishing channel type.

We tested the hypothesis that the five *a priori* channel types exhibit differences in channel geometry using PerMANOVA (Anderson, 2001, 2005) via the *adonis* function within the *vegan* package in R (Oksanen et al., 2011; R Core Team, 2012). Euclidean was the distance measure, and 9999 permutations were used (Oksanen et al., 2011).

Nonmetric multidimensional scaling using the Euclidean distance measure and random starting coordinates, Monte Carlo tests for dimensionality were performed with 250 permutations of observed and randomized data from the 86 study reaches in YPG. Dimensionality of the final solution was selected to minimize stress values. Applicability of the ordination was verified using axis scores for the validation data set of 15 study reaches in BMGR. Reach-scale geomorphic and hydraulic variables were correlated against axis scores, using Pearson correlation. Ordination was performed using PC-Ord (McCune and Mefford, 1999; version 5.10, MjM Software, Gleneden Beach, OR, USA).

Classification tree analysis was used to provide the potential ranges of values for hydraulics and geometry that can be expected for each channel type. The classification tree was grown with training data from the 86 study reaches in YPG, using 15-fold cross-validation and the Gini index as the splitting rule, and validated using the 15 study reaches from BMGR. The final tree was pruned to minimize the relative cost (0.417) (Salford Predictive Modeler v6.6, 1998). This analysis provides a way to test the basis of the *a priori* classification by predicting channel type based on hydraulics and channel geometry.

Linear discriminant analysis (LDA) was used to investigate the potential strength in the classification by predicting channel type based on channel geometry and hydraulics. The LDA was conducted using moment calculations in the *lda* function of the *MASS* package in R statistical software (R Core Team, 2012; Ripley et al., 2012). The discriminant criterion was developed using 86 study reaches at YPG, while 15 study reaches at BMGR were used as an external validation data set. Internal validation of the discriminant function was conducted using *predict* in the *MASS* package of R-studio to determine the stream type of the 86 study reaches used to develop the discriminant function. External validation of the discriminant function was conducted by predicting the stream type for 15 study reaches surveyed at BMGR. Internal and external validation results in optimal and actual hit rates (Manly, 2000), which indicate the ratio of successful predictions of stream type over the total number of classification attempts.

4. Results

4.1. Study reach characteristics

Contributing drainage areas and stream gradients (0.004–0.58) for all 101 study reaches capture the progression of channel types through distinct zones from small, steep, erosional mountainous bedrock channels to broad, depositional braided alluvial valleys. Boxplots illustrate relative differences in the five stream types with respect to all eight variables examined, particularly strong differences in W/D, S, Ω, τ, and ω (Fig. 5). The most pronounced differences in channel geometry and hydraulics occur between bedrock (BK) and braided (BD) channels (Fig. 5). The BD and BK reaches are easily distinguished from other channel types by W/D and τ, respectively. As expected, BK channels have much higher gradients and lower W/D ratios, whereas BD channels have lower gradients and higher W/D ratios. The BD, BK, and PH channels form relatively tight groups with respect to W/D and Ω, whereas the BA and IA channels contain more variability and overlap with less distinct grouping (Fig. 6). The BA and IA channels are more closely related and not easily distinguished from one another (Figs. 5, 6).

4.2. Variable selection

Individual one-way analysis of variance (ANOVA) indicated that group means of each predictor variable differed significantly between the five stream types ($p \leq 0.001$), with the exception of median grain size (d_{50}, $p = 0.147$). Multiple comparisons of group means of each variable indicated that the best variables for distinguishing between channel types are width-to-depth ratio (W/D), stream gradient (S),

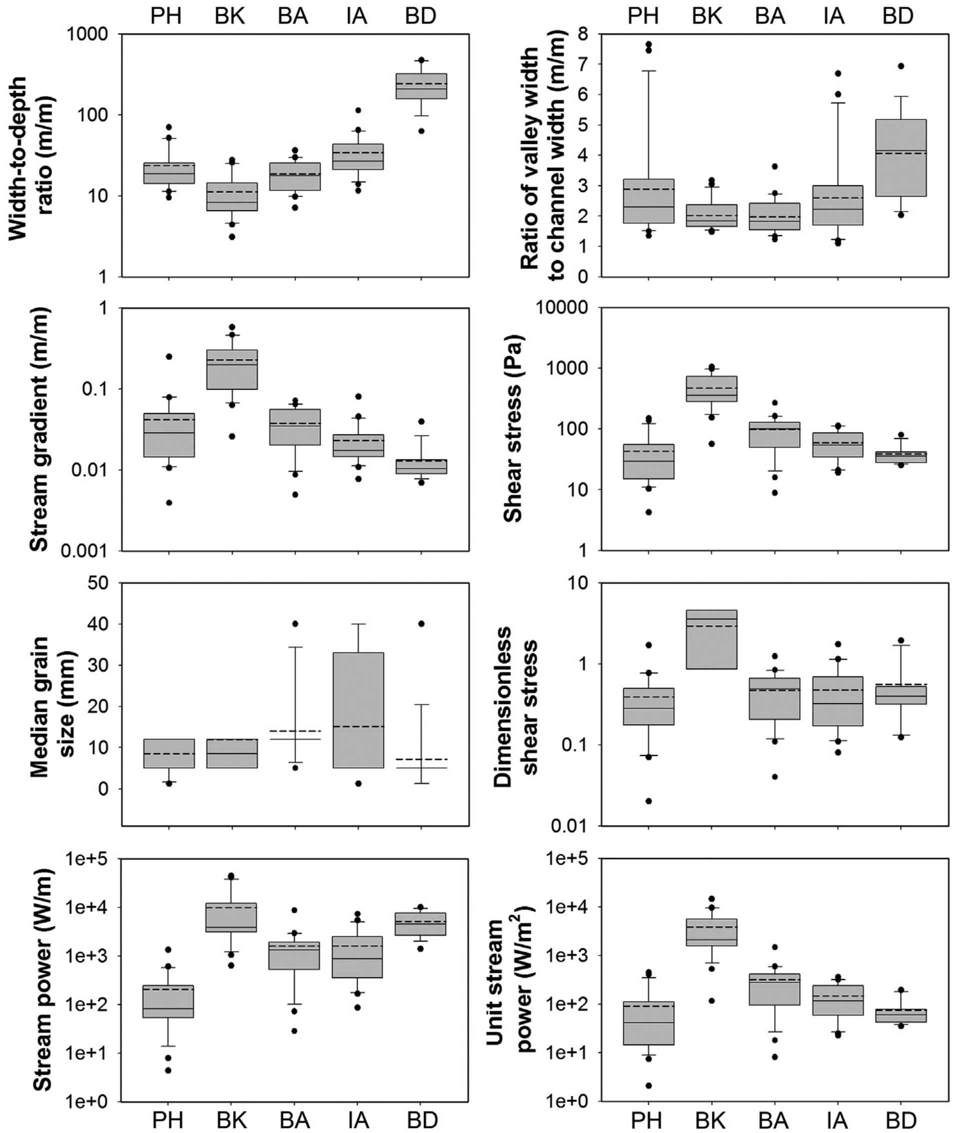

Fig. 5. Box plots of eight variables (W/D, W_v/W_c, S, τ, d_{50}, τ^*, Ω, ω) for the five channel types on the horizontal axis; piedmont headwater (PH), bedrock (BK), bedrock with alluvium (BA), incised alluvium (IA), and braided (BD)channels from 101 study reaches surveyed at YPG and BMGR. Values are log-transformed, box center lines indicate the median, dashed lines indicate means, box ends are the 25th and 75th percentiles, and whiskers extend to the 5th and 95th percentiles.

stream power (Ω), shear stress (τ), and unit stream power (ω). Median grain size (d_{50}) and dimensionless shear stress (τ^*) lacked the power to distinguish stream types and were eliminated from the analyses. To reduce the likelihood of confounding cross correlation between predictor variables, measures of stream competence (τ, Ω, ω) were reduced to τ and Ω. Although both Ω and τ incorporate channel slope (S) by definition and are correlated with S ($R^2 = 0.25$ and 0.82, respectively), each of these variables provided information crucial for distinguishing particular channel types. Shear stress (τ) was retained as a predictor variable in the model because it encompasses depth of flow and easily distinguishes bedrock from other channel types. First-order approximations of stream power (Ω) could be used to distinguish piedmont headwater channels from other stream types.

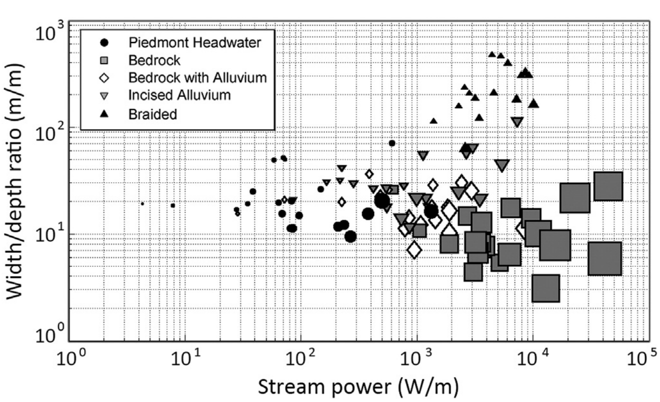

Fig. 6. A scatter plot of reach-average width-to-depth ratio versus stream power for 101 study reaches illustrates grouping among stream types. Marker size indicates estimated relative reach-average shear stress.

A two-dimensional NMS ordination minimized mean stress at 3.52 ($p = 0.004$) for 86 study reaches in YPG. The NMS scores for the validation data set from BMGR using this solution exhibited a mean stress of 3.53 and corresponded closely to those from YPG (Fig. 7). Separation of study reaches along axis 1 was dominated by differences in τ ($r = -0.93$) and Ω ($r = -0.91$), whereas separation along axis 2 was driven by width-to-depth ratio ($r = 0.94$) (Fig. 7; Table 2). Stream gradient exhibited moderate correlations with both axes scores ($r_1 = -0.71$, $r_2 = -0.68$). Entrenchment ratio was weakly correlated with both axes and is a poor indicator variable. These ordination results validate the use of W/D, S, Ω, and τ for additional multivariate analyses.

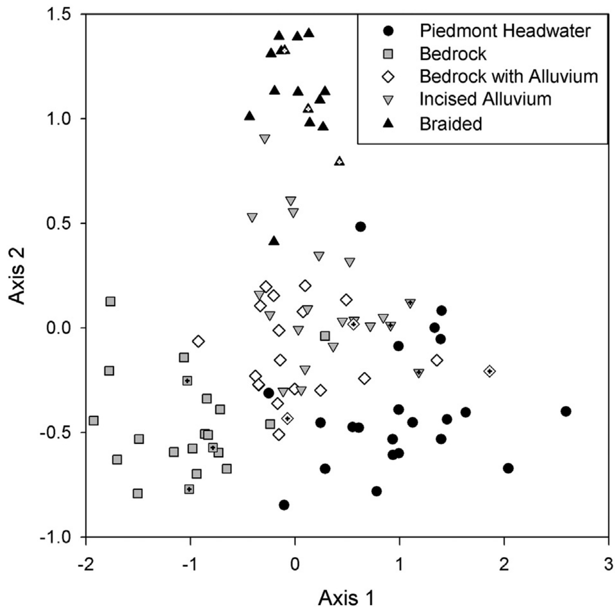

Fig. 7. Nonmetric multidimensional scaling ordination plot of 101 study reaches for five variables (S, τ, W/D, Ω, and W_v/W_c). Crossed symbols denote the external validation data set of 15 study reaches from BMGR, whereas solid symbols (without crosses) indicate the calibration data set of 86 study reaches from YPG. Axis 1 is dominated by τ ($r = -0.93$) and Ω ($r = -0.91$), whereas axis 2 is dominated primarily by width-to-depth ratio ($r = 0.94$) (Table 1).

4.3. Hydraulic and geomorphic differences among channel types

We used multivariate analyses to address our primary objective and to test our hypothesis described in Section 3.2. PerMANOVA results indicated that multivariate mean channel geometry and hydraulics are not equal for all five stream types ($p = 0.0001$, F-statistic $= 362$). This allowed us to reject the null hypothesis that channel types were identical.

To identify differences in channel type, linear discriminant analysis (LDA) was conducted using W/D, S, Ω, and τ for the learning data set of 86 study reaches at YPG. This discriminant function correctly predicted 77% of sites (Table 2). The BA and IA channel types were misclassified more than other channel types using LDA on the data from YPG. The majority of misclassifications occurred within prediction of BA (67% BA hit rate) and IA (50% IA hit rate) study reaches, such that these stream types were confused for one another (Table 2).

External validation for the testing data set using the same discriminant function resulted in successful prediction of 73% of the 15 study reaches surveyed at BMGR. The PH, BK, and BD channels were correctly classified through external validation in every case (100% hit rate). Misclassifications occurred for BA and IA channels when they were confused for one another or misclassified as PH channels (Table 2).

The classification tree (CT) determined the relative strength of variables to be the following: $S > W/D > \Omega > \tau$. The CT model distinguished 92% of BD reaches by $W/D > 118$ (Fig. 8). For channels with $W/D < 118$, 94% of BK reaches were identified by $\tau > 152$ Pa. Approximately 68% of PH channels were distinguished by $\Omega < 217$ W/m, $\tau < 152$ Pa, and $W/D < 118$. Of the remaining study reaches, 67% of IA channels had $S < 0.02$. The areas under the receiver operator curves for the entire CT were 0.93 and 0.88 for the learning and test data sets, respectively. Successful prediction in the learning data set from YPG for correctly identifying PH (68%), BK (94%), BA (67%), IA (67%), and BD channels (92%) resulted in an overall hit rate of 77%, which equates to an overall prediction error of 23%.

Table 1
Pearson correlation coefficients for nonmetric multidimensional scaling ordination among reach-scale geomorphic and hydraulic variables for 86 study reaches at YPG.

Axis	1	2
Stream gradient	−0.71	−0.68
Width/depth	+0.24	+0.94
Entrenchment ratio	+0.23	+0.30
Shear stress	−0.93	−0.41
Stream power	−0.91	+0.36

5. Discussion

Channel geometry and reach-scale hydraulics can allow the differentiation of ephemeral stream types in arid regions and form the basis for a channel classification. We observed higher stream gradient and shear stress in bedrock channels than in alluvial channel segments, which are known for streams in diverse environments (Tinkler and Wohl, 1998; Wohl and David, 2008). Lower shear stress and stream gradient, and greater width-to-depth ratios and stream power, are known to occur in braided alluvial ephemeral channels (Bull, 1977; Graf, 1988a; Tooth, 2000; Reid and Frostick, 2011). Because channel parameters influence sediment transport (Powell et al., 1998; Tucker et al., 2006), surface/subsurface hydrologic interactions (Schick, 1986), structure and function of riparian habitat and vegetation communities (Birkeland, 1996; Hupp and Osterkamp, 1996; Merritt and Wohl, 2003; Al-Rowaily et al., 2012), and sensitivity to disturbance (Montgomery, 1999; Brierley and Fryirs, 2005), they provide insight into the physical and biological processes occurring in dryland ephemeral channels.

Channel geometry and hydraulic parameters can be used to infer differences in disturbance regime, channel adjustment to disturbance, and ecological sensitivity. Water and sediment storage appear to increase from negligible amounts in bedrock channels to progressively higher amounts in piedmont headwater, bedrock with alluvium, incised alluvium, and braided channels based on relative values of shear stress, stream power, and width/depth ratio among these channel types. Consequently, disturbances such as floods or debris flows that alter water and sediment inputs to channel segments are more likely to completely restructure channel and riparian habitat in piedmont headwater and bedrock with alluvium channels, whereas incised alluvium and braided channels more likely experience localized erosion, deposition, and restructuring of habitat. In contrast, the resistant channel boundaries and high transport capacity of bedrock reaches would probably result in minimal geomorphic adjustments to allogenic disturbances. We also expect the smaller drainage areas of bedrock, piedmont headwater, and bedrock with alluvium reaches to result in more frequent flood disturbance than in incised alluvium and braided reaches occupying the lower portions of channel networks. Small headwater catchments experience more frequent storm coverage and rapid runoff generation than downstream portions of larger channel networks, which require more spatially extensive and prolonged rainfall to generate floods (Tucker et al., 2006; Shaw and Cooper, 2008).

The combined effects of localized erosion and deposition during flow events, infrequent disturbance, and greater alluvial storage capacity are reflected in the greater diversity of woody riparian vegetation along incised alluvium and braided channel segments within the study area (Merritt and Wohl, 2003) and in other ephemeral channel networks (Hupp and Osterkamp, 1996; Shaw and Cooper, 2008). Braided and incised alluvium channels are more geomorphically complex (Figs. 5, 6) than steeper, confined reaches and therefore have more capacity to absorb changes in water and sediment inputs without substantial morphologic change. Because flood disturbances are less likely to completely replace existing alluvial surfaces and remove riparian vegetation in braided channel segments, this channel type may be more resilient to natural disturbances. However, human-induced disturbances such as vehicular traffic and military training are more likely to alter channel geomorphology and remove riparian vegetation. Braided channels could be considered less resilient to such disturbances compared to

Table 2
A confusion matrix for prediction of channel types based on W/D, S, Ω, and τ for linear discriminant analysis (LDA; values on top) and a classification tree model (CT; values in parentheses); numbers before each comma indicate results for the training data set of 86 study reaches at YPG, whereas bold numbers following each comma indicate results for the test data set of 15 study reaches at BMGR.

		Predicted channel type					Hit rate		
		Piedmont headwater	Bedrock	Bedrock with alluvium	Incised alluvium	Braided	Learning data set (YPG)	Test data set (BMGR)	Model
Actual channel type	**Piedmont headwater**	17, **3**	0, **0**	1, **0**	1, **0**	0, **0**	90%	100%	LDA
		(13, **3**)	(0, **0**)	(5, **0**)	(1, **0**)	(0, **0**)	(68%)	(100%)	CT
	Bedrock	0, **0**	16, **3**	1, **0**	1, **0**	0, **0**	89%	100%	LDA
		(0, **0**)	(17, **3**)	(1, **0**)	(0, **0**)	(0, **0**)	(94%)	(100%)	CT
	Bedrock with alluvium	3, **1**	0, **0**	12, **1**	3, **1**	0, **0**	67%	33%	LDA
		(1, **1**)	(2, **0**)	(12, **1**)	(3, **1**)	(0, **0**)	(67%)	(33%)	CT
	Incised alluvium	2, **1**	0, **0**	6, **0**	9, **1**	1, **1**	50%	33%	LDA
		(0, **2**)	(0, **0**)	(6, **0**)	(12, **1**)	(0, **0**)	(67%)	(33%)	CT
	Braided	0, **0**	0, **0**	0, **0**	1, **0**	12, **3**	92%	100%	LDA
		(0, **0**)	(0, **0**)	(1, **0**)	(0, **1**)	(12, **2**)	(92%)	(67%)	CT
					Total prediction hit rate		**77%**	**73%**	**LDA**
							(77%)	**(67%)**	**CT**

bedrock channels, which mostly lack riparian vegetation and have resistant channel boundaries. Our classification of channel geometry may be a useful proxy for river ecosystem characteristics, such as riparian vegetation extent and sensitivity to disturbances, when managing riverine ecosystems in the study area.

5.1. Misclassifications

The bedrock with alluvium and incised alluvium channels are the most similar based on field measures, and our analyses often misclassified them. However, we believe that these two channel types warrant distinction. Aggregating bedrock with alluvium and incised alluvium channels into a single reach type resulted in decreased hit rates for all stream types using the linear discriminant function. Additionally, we observed geomorphic differences between these two reach types that were not captured by our data. These differences between bedrock with alluvium and incised alluvium channels likely have implications for channel evolution, riparian vegetation community structure, and disturbance. Incised alluvium channels often have more vegetated point bars and well-developed floodplain surfaces with abundant riparian vegetation compared to bedrock with alluvium channels. Although the measured channel geometry and reach-scale hydraulics of these reach types are similar, differences in boundary material erodability would likely lead to different sensitivity to natural and anthropogenic disturbance.

5.2. Transitional states

Spatial and temporal transitional states can pose difficulties in identifying the appropriate ephemeral channel type through quantification of the data and qualitative identification in the field. Although visual distinction of most channel types in the field is relatively straightforward (e.g., bound by bedrock, braided, initiate on the piedmont), ambiguity lies in the distinction between bedrock and bedrock with alluvium channels. For this reason, we define bedrock with alluvium channels to contain a persistent, significant cover of continuous alluvium for >50% of the channel reach. This, however, is subjective to the time scale at which channels of interest are considered. We add the additional modifier for presence of bedforms and/or point bar development, which should indicate some level of persistence of the alluvial cover.

Although attempts were made to minimize inclusion of transitional reaches in the data, difficulties arise with transitional states along the spectrum of channel evolution on which we have imposed a discrete classification. Users must consider potential transitional states when applying this classification. When the designation of channel type is in question as a result of a potential transitional state, we recommend considering the range of S, W/D, Ω, and τ values found in this study for more than one possible channel type (Fig. 5). It may also be of interest to investigate the direction in which the transition is trending in order to improve land management or restoration efforts.

5.3. Floodout zones

Transitional states may also create conditions where channel characteristics become undefined or indistinct, such as the phenomenon referred to as floodout zones in Australia (Tooth, 1999, 2000; Grenfell, 2012). Braided channels exist at BMGR as short segments that develop distributary channels and disappear into unconsolidated alluvium. We did not find this pattern at YPG, but it may occur in surrounding regions. Braided channel reaches located at BMGR appeared to occur only in partially confined zones bounded by mountains. As confinement of bedrock uplands decreased and valley width increased along a study reach in BMGR, for example, infiltration appeared to result in a floodout zone downstream of the study reach where the wash became entirely unconfined. Dust and Wohl (2010) identified thresholds for braiding, which distinguish channel types with regard to width-to-depth ratio and unit stream power. A similar threshold may exist for floodout zones, such that accommodation space becomes infinitely large and shallow sheet flow infiltrates readily into unconsolidated alluvium, leaving minimal to no trace of channelized flow. The lack of surface channel geometry in floodouts limits their comparison and inclusion in our classification, and we suggest that these features be considered as a landscape unit rather than a channel type.

5.4. Application of the classification system

Both the classification tree and discriminant analysis provide a way to test the strength of this *a priori* classification by predicting channel type based on channel geometry and hydraulics. This alone is not the way we intend the classification to be used, but rather use it to test the validity of such a classification. Given a high success rate of prediction using these methods, land use managers can then assume a range of values in channel geometry and hydraulics that can be expected for a channel of interest given qualitative identification of the channel type in the field or using remotely sensed imagery and DEMs.

We provide a dichotomous key to distinguish channel types (Fig. 9). Channel type can be identified in the field using the dichotomous key or GIS data if the necessary imagery, geologic layers, and DEMs are available. Braided channels are easily distinguished using channel planform from aerial imagery. Bedrock with alluvium and incised alluvium channels can be identified using geologic maps or field reconnaissance to separate bedrock versus unconsolidated alluvium channel boundaries. Piedmont and alluvial fan surfaces are distinguishable using aerial imagery and may be apparent in some regions when contrasted with

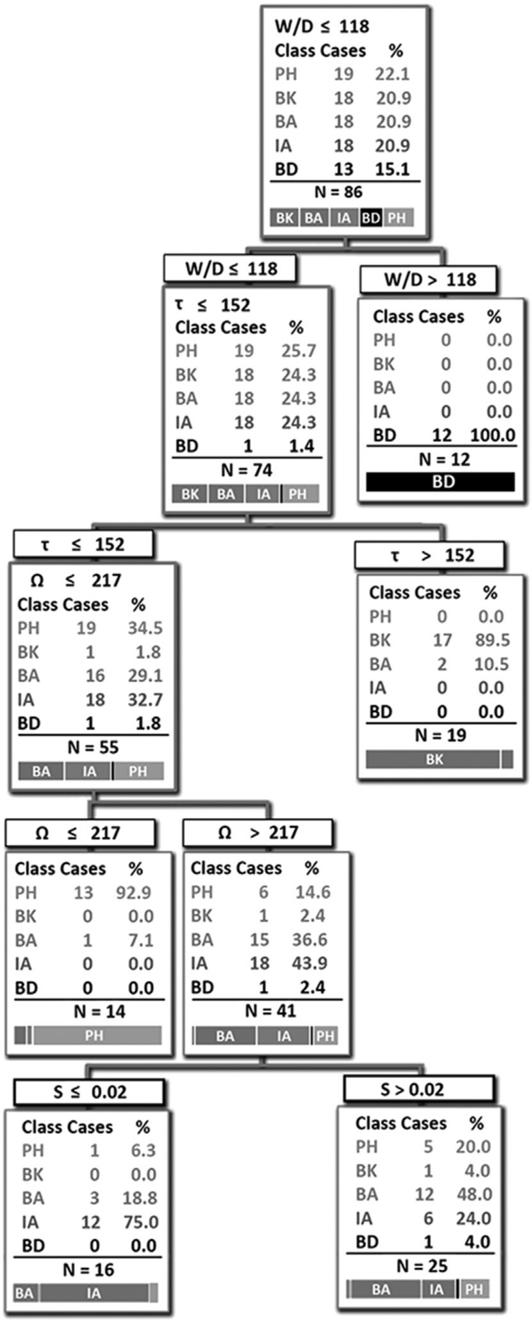

Fig. 8. Classification tree (Salford Predictive Modeler v6.6, 1998) based on 86 study reaches at YPG identifying cutoff points for *W/D*, *S*, *Ω*, and *τ* used to distinguish the five channel types: piedmont headwater (PH), bedrock (BK), bedrock with alluvium (BA), incised alluvium (IA), and braided (BD) channels. *N* represents the sample size for each node, and percentages indicate the relative distribution of each stream type within each node.

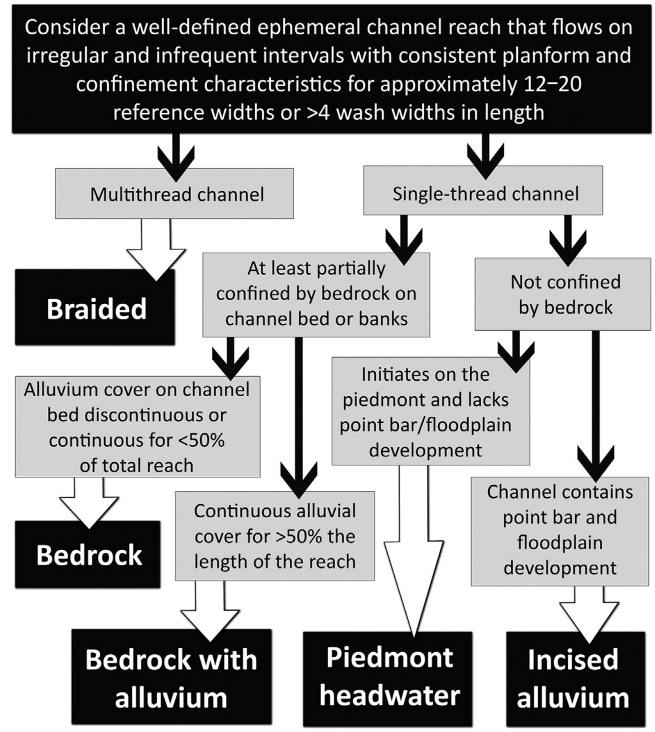

Fig. 9. Dichotomous key to identify arid-region ephemeral stream geomorphic channel types based on qualitative descriptors. Reference widths refer to the width of the channel at a stage that represents a discharge responsible for maintaining contemporary channel geometry. Wash width refers to the valley bottom width at the confining boundaries of a braided channel.

adjacent desert pavement. Headwater channels that initiate on piedmont or bedrock surfaces are easily distinguished from one another using geologic and geomorphic surfaces with the appropriate surveys and GIS layers mentioned above. We encourage remotely sensed applications of this classification to include field visits for a subset of channel segments in the field to ensure correct identification of channel types.

Although we did not formally analyze the spatial distribution of each channel type, qualitative analysis from field observations, digital elevation models, geologic maps, and aerial imagery indicate a generalized spatial distribution of channel types relative to mountainous uplands. Within YPG and BMGR, exposed bedrock is limited to mountain highlands, while unconsolidated alluvial bodies are more prevalent with increasing distance from mountains. Thus braided and incised alluvium channels increase in abundance with distance from mountains. Piedmont headwater channels occur most commonly along the margins of broad valleys and intermountain basins. The spatial distributions of reach types will likely differ in other physiographic regions. For example, bedrock or bedrock with alluvium channels may occur in incised canyons commonly found in lowlands of flat sedimentary landscapes such as the Colorado Plateau.

Our classification should be tested and applied in other arid regions. We anticipate this channel classification to be applicable to dryland ephemeral streams around the world, even though the range of values in channel geometry and hydraulic variables associated with each channel type will vary with climate, physiography, geology, and vegetation. Applications in arid regions that differ substantially from the Sonoran Desert may require similar analyses to determine parameter ranges of channel types.

6. Conclusions

Stream classifications provide guidance to understanding and measuring the physical response in channel geometry and structure and function of aquatic and riparian habitat with regard to anticipated frequency and magnitude of flows. A dearth of data concerning the temporal and spatial variability of ephemeral streams in arid regions currently limits understanding of channel response and associated riparian habitat, and researchers lack the broadly applicable vocabulary necessary to discuss these relationships. We have presented a geomorphic classification of ephemeral channels in arid regions based on planform, the degree of confinement, and the composition of confining material to contribute to understanding of dryland fluvial systems. Our analyses indicate that five *a priori* channel types differ significantly with respect to width-to-depth ratio, stream gradient, stream power, and shear stress despite limited accuracy of a few measured and derived variables based on the reference stage. These results illustrate meaningful differences in channel geometry among the five stream types and provide a conceptual framework to infer fluvial processes, assess hydrologic and ecological sensitivity to disturbance and climate change, and guide management and restoration activities throughout ephemeral stream networks.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.geomorph.2014.06.005.

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