Geomorphology 221 (2014) 164–175

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

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

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ARTICLE INFO

Article history:
Received 20 September 2013
Received in revised form 31 May 2014
Accepted 2 June 2014
Available online 9 June 2014

Keywords:
Stream classification
Desert stream
Ephemeral channel
Braided channel
Channel geometry
Arid region

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.

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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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http://dx.doi.org/10.1016/j.geomorph.2014.06.005
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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

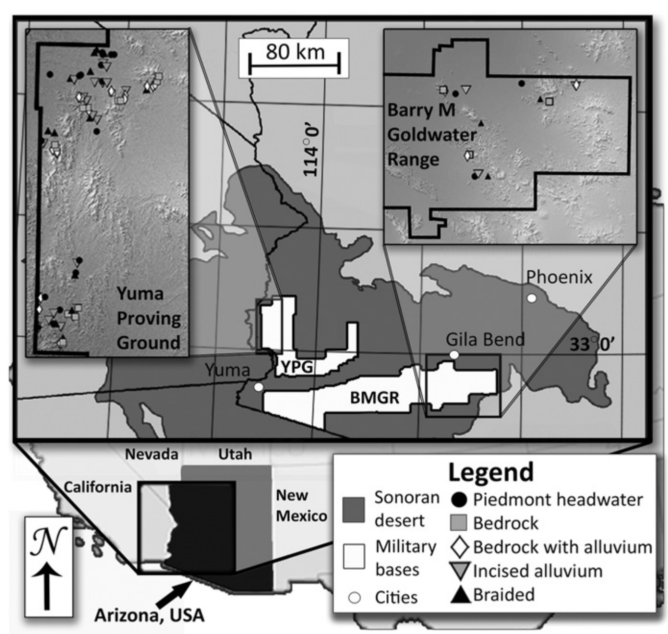

Fig. 1. Locations of 101 study reaches within the U.S. Army Yuma Proving Ground (YPG) and Barry Goldwater Air Force Range (BMGR) in southern Arizona within the extent of the U.S. Sonoran desert, as defined by Brown et al. (2007).

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