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Viewpoint

Casualty of historic arroyo incision in the southwestern United States

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ABSTRACT

Arroyos in the American southwest are defined as steep-walled, flat-floored trenches, typically cut into alluvium. Intensive investigation of arroyos for more than a century has shown that arroyo cutting events have been temporally concentrated during the Holocene, the most recent (historic) interval occurring between 1850 and 1915; the 1880s and early 1900s were particularly important periods of formation. The restricted period of historic cutting suggests that their formation is related to semi-synchronous changes in environmental conditions throughout the southwestern U.S. However, determining causality is plagued by multiple, temporally overlapping drivers, that vary in magnitude and intensity over the region and that produce non-linear and divergent geomorphic responses that often lag well-behind the disturbance. The lag in response times is a result of sequential adjustments in vegetation, runoff, sediment yield, groundwater-surface water interactions, and/or the propagation of geomorphic adjustments through the system. In light of these difficulties, it may be more productive from a management perspective to determine the controls on valley/arroyo system response to disturbance and the potential impacts of these geomorphic responses on ecosystem conditions than to concentrate on the causality of arroyo formation.

1. Introduction

Early explorers in the American southwest referred to narrow, steep-walled, flat-floored excavations cut into low-relief alleviated valleys as arroyos. Morphologically, arroyos consist of a trench, generally collocated with, and cut into, the valley floor, that is often meters to a few 10s of meters deep. Spatially, arroyos may extend for 10s of kilometers along the axis of a drainage basin. Many arroyos, however, occur as a discontinuous channel bound upstream by a headcut and downstream by an aggradational, fan-shaped feature devoid of a trench. These discontinuous arroyos commonly occur in groups, forming an alternating sequence of aggradational "in-valley fans" and erosional trenches. Although the majority of investigations have focused on arroyos that are collocated with alleviated valleys, both continuous and discontinuous arroyos have been described on piedmonts and within low-order tributaries, making the distinction between arroyos, gullies and alluvial fan systems rather vague.

Arroyos of the American southwest, including those in Arizona, New Mexico, southern Colorado, and Utah, are some of the most intensively studied fluvial systems in the world (Macklin et al., 2012; Harden et al., 2010). Arroyos have, however, been identified in wide range of other semi-arid and arid environments, both in the U.S. (e.g., southern California, central Nevada and southeastern Washington) and globally (e.g., Bolivia, South Africa, and Australia).

An overwhelming majority of the studies in the U.S. have focused on the nature, magnitude, timing, and causes of arroyo cutting events. Nonetheless, it is widely recognized that periods of entrenchment are separated by periods of aggradation, creating a cyclical pattern of aggradation and erosion consisting of four phases (Graf, 1983; Wells, 1987): (1) an initial phase in which a stream channel is absent or flowing on the valley floor, (2) a phase of channel incision, (3) a phase of trench enlargement, combined with the development of fluvial landforms (e.g., floodplains) on the floor of the trench, and (4) a phase of aggradation that fills the trench until the channel rests once again on the valley floor. It is generally accepted that arroyo cutting and filling is associated with drivers that have resulted in a threshold crossing event, but the discussion of the predominant drivers in the southwestern U.S. has become one of the most intensively debated topics in fluvial geomorphology.

2. Overview of causative factors

The timing of historic arroyo cutting in southwestern U.S. has been extensively analyzed using a wide range of historic documents, complimented by geomorphic, stratigraphic, dendrochronologic,

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and archeologic analyses. Regionally, there is a consensus that arroyo cutting occurred primarily between about 1850 and 1915. Within this 65-year period, many arroyos formed during the 1880s and, to a lesser degree, from 1905 to 1915 (Bryan, 1925; Antevs, 1952; Cooke and Reeves, 1976; Graf, 1983; Miller and Kochel, 1999; Aby, 2017). It follows, then, that any analysis of arroyo formation must explain why arroyo cutting was concentrated during these periods. Three primary drivers of incision have been be proposed: (1) intense anthropogenic disturbance associated with Spanish and Anglo-European settlement, (2) short-term climatic variations, and (3) intrinsic geomorphic adjustments in the fluvial system that led to the crossing of a geomorphic threshold. Recent tectonic activity is limited in the area, and its influence on incision is considered negligible. Specific arguments for citing each of these three drivers as the predominant cause of historic arroyo formation have been reviewed by Graf (1983), Miller and Kochel (1999), and more recently, Aby (2017). A few key points of importance to the following discussion are highlighted below.

2.1. Anthropogenic activities

The most commonly cited anthropogenic driver of arroyo cutting, particularly by early investigators, was overgrazing associated with the introduction of large numbers of livestock to the American southwest, especially during the 1880s. The causative link between overgrazing and arroyo development is based on two arguments: (1) a temporal correlation seemed to exist between the introduction of livestock and regional arroyo cutting (Bailey, 1935; Cooperider and Hendricks, 1937), and (2) livestock was presumed to have compacted the catchment soils and severely degraded hillslope and valley floor vegetation, allowing for an increase in runoff capable of eroding valley alluvium. A less commonly cited human induced cause of arroyo formation was the development of what Cooke and Reeves (1976) referred to as drainage concentration features (DCFs). This term refers to a wide range of features such as cattle trails, unpaved roads, irrigation structures, and railroad embankments that allowed for the concentration of flow on the valley floor, thereby increasing its erosive ability.

There is little debate that human activity can initiate the formation of both continuous and discontinuous arroyos. For example, prior to 1890 the Santa Cruz River valley in Arizona was characterized by short, discontinuous arroyos and shallow swales (Betancourt and Turner, 1988) that were not significantly enlarged by floods in 1886, 1887, or 1889 (Hastings, 1959). In August 1889, Sam Hughs excavated a small ditch into the alluvial fill in the hope that future runoff events would enlarge the trench so that it would intercept groundwater and provide a continuous source of water for irrigation. In 1890, extensive floods widened and extended the ditch for several kilometers along the valley floor. Subsequent events led to arroyo extension to that allowed the trench to coalesce with other discontinuous arroyos so that by 1930 the Santa Cruz River (arroyo) was 60 to 70 km long (Betancourt and Turner, 1988).

In spite of such observations, the argument that human induced changes to the environment can serve as a universal explanation of arroyo cutting for the American southwest as a whole is plagued by several shortcomings. These limitations include (1) a lack of hydrophysical data that demonstrate, on a regional basis, that changes in channelized runoff as a result of overgrazing occurred, (2) the introduction of livestock into New Mexico and Arizona by Mexican herders approximately four decades before the onset of significant arroyo development (Cooperider and Hendricks, 1937; Denevan, 1967; Graf, 1983), (3) the development of arroyos in areas where grazing had not occurred prior to arroyo incision (Peterson, 1950), (4) the lack of identified human disturbances, including DCFs, in areas of arroyo formation, particularly in lower order tributaries of more rugged terrain, and (5) the development of arroyos prior to the arrival of Spanish/Anglo-settlers (see, for example, Wells, 1987 and Balling and Wells, 1990). In addition, human activities cannot explain the widespread development of paleoarroyos preserved in alluvial valley fills (described in more detail below), and which also appear to have rapidly formed during specific times spaced throughout the Holocene (see Miller and Kochel, 1999).

A less commonly recognized problem in citing anthropogenic activity as a cause of arroyo cutting is that a simple spatial and/or temporal correlation between arroyo development and human activity does not necessarily indicate a cause-effect relationship. An example is provided by recent detailed geomorphic (Miller et al., 2011), hydrogeologic (Lord et al., 2011), and biotic (Chambers et al., 2011) analyses of numerous stream systems, such as the Reese River Valley, in central Nevada. The first well-documented episode of cutting along the Reese River occurred in the early 1900. However, the development of other discontinuous arroyos occurred throughout the 20th and 21st centuries, demonstrating that the propagation of arroyos through a catchment can take decades. A number of these discontinuous arroyos were clearly produced by DCFs, as their headcuts terminate upstream in cattle trails and/or roads and the development of arroyos can be seen to parallel such trails on sequential aerial photographs. In other cases, however, discontinuous arroyos in the area were initiated within wet meadow ecosystems, and appear to be related to the complex interplay between localized changes in the water table, burrowing animals, groundwater piping, and other processes unrelated to human activities (Miller et al., 2011). These arroyos were often associated with springs positioned along narrow, steep reaches of the valley floor (Miller et al., 2011), and which released enough runoff during relatively wet periods to erode the alluvium. Thus, recent formation of discontinuous arroyos in the area was related to both natural and anthropogenic drivers. Regardless of cause, local land-owners and land-managers recognized that shallow swales on the valley floor had the potential to develop into headcuts and expand into lengthy, discontinuous arroyos. To prevent such erosion from occurring, they took preventative actions, many of which exacerbated arroyo expansion (Fig. 1). The point is that in some cases, within the same valley, human activities initiated arroyo cutting, and natural processes helped facilitate it, whereas in others, natural processes initiated arroyo formation, and human activities facilitated their expansion. Which process was the facilitator and which was the initiator of arroyo cutting at a site could not be determined by means of a simple spatial correlation of the anthropogenic and/or natural features. Such intermingling of natural and anthropogenic drivers was likely to be widespread during the period of historic arroyo formation throughout the southwestern U.S.

2.2. Changes in climate

Climate, particularly precipitation, exerts a significant influence on geomorphic processes, primarily through its control on runoff, sediment generation and, over longer time-scales, vegetation. The proposition that historic and pre-historic (paleo) arroyos resulted from short-term (multi-year to century-scale) changes in climate dates back at least to the 1880s when Dutton (1882) argued that arroyos resulted from an increase in precipitation which enhanced runoff that led to valley incision. Bryan (1922) originally accepted this hypothesis. However, he subsequently argued that arroyos resulted from a change from wetter to drier conditions, the latter of