Reconciling arroyo cycle and paleoflood approaches to late Holocene alluvial records in dryland streams

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**A B S T R A C T**

A century of research into the environmental records of alluvial-valley fills in drylands has led to new theories about landscape response to climate change and cultural evolution over the Holocene. In a largely separate line of inquiry, paleoflood hydrologists have scoured bedrock canyons for slackwater deposits, extending the flood record and exploring their climatic significance. Both approaches rely on the analysis and dating of late Holocene alluvium, sometimes along the same drainages, yet they differ in the geomorphic setting in which they should be applied. Studies of arroyo cut-and-fill cycles are focused on broad alluvial valleys, whereas paleoflood hydrology has been focused mainly in narrow bedrock canyons.

With a focus on the southwestern U.S., we review and compare the fundamentals of these two approaches and their paradigmatic disconnect, and then discuss potential linkages that could lead to a more complete understanding of how dryland streams adjust to external stimuli. Recent regional compilations provide insight into the broader relation between the two record types over entire physiographic provinces. Meanwhile, new tools such as OSL dating, short-lived isotopes, and improved hydraulic modeling are paving the way for refinement and reconciliation of the two approaches within individual drainages. The relation between past arroyo cut-and-fill cycles and paleofloods must be thoroughly explored if we are to fully understand how drainages will respond to a changing climate over the coming decades to centuries.

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1. Introduction

Holocene alluvial deposits stored along dryland streams provide records of environmental change in their watersheds. Careful interpretation of these alluvial archives can reveal past landscape responses to changes in climate, hydrology, and cultural activity (e.g. Bryan, 1925). Such records are especially pertinent because they often record changes similar in scale to those predicted for the upcoming century (e.g. Hughes and Diaz, 2008).

Most studies of alluvial deposits in drylands fall under one of two paradigms. The first stems from a long history of study of alluvial cut-and-fill cycles and the “arroyo problem” as reviewed below. The second, younger approach is based on the analysis of slackwater sediments to reconstruct paleoflood frequency and/or magnitude (e.g. Patton et al., 1979; Baker, 2008). Although each approach is recognized by its practitioners as applicable to Holocene alluvial records in particular settings, confusion remains about their appropriate application and relation to one another along and across drainages. In fact, these contrasting approaches may lead to quite different interpretations of the same alluvial deposits, yet they have the potential to be complementary rather than contradictory. Reconciliation of these distinct yet fundamentally related approaches is essential for a complete and systematic understanding of sensitive dryland streams in a changing climate.

Geomorphic setting is the key factor distinguishing these two scientific approaches and record types (Fig. 1). In the example of the southwestern U.S., stream valleys range from broad, unconstricted reaches a kilometer or more wide to bedrock slot canyons only meters wide. Often, such variation in valley geometry can be seen along individual drainages. Large volumes of valley-fill alluvium can be stored along the broader reaches, where bedrock exerts little to no control on channel form. Early workers in the southwestern U.S. recognized that these valley-fills record episodes of aggradation and degradation on the scale of centuries or millennia, and that these have key relations to paleoclimate and archaeology (e.g.
2. Holocene arroyo dynamics

2.1. Historic arroyo cutting

Geologists and archeologists have studied the alluvial records of semiarid streams for over a century (Dodge, 1902). Much of this work was motivated by a widespread episode of channel incision in the American Southwest from \( \sim 1880-1920 \) AD. Over these few decades, drainages incised up to 30 m into their alluvium, leaving former floodplains behind as terraces. Because many farms and settlements had been built on these surfaces in the preceding decades, erosion accompanying arroyo cutting resulted in substantial property damage, agricultural losses, and abandonment of entire communities (Bryan, 1929; Peterson, 1950; Cooke and Reeves, 1976).

2.2. Mechanisms of arroyo formation

The causes of historic arroyo cutting have been the subject of longstanding debate in the literature. A number of reviews discuss the variety and evolution of hypothesized mechanisms over the past century (e.g. Cooke and Reeves, 1976; Graf, 1983; Miller and Kochel, 1999); and though we include a brief review below, we defer to these works for a more exhaustive treatment of the issue.

2.2.1. Anthropogenic

Early workers suggested that land use changes during Anglo-American settlement of the Southwest triggered arroyo incision (e.g. Dodge, 1902; Huntington, 1914; Bailey, 1935). Specifically, the introduction of livestock grazing accompanying settlement had disturbed vegetation and compacted sediment on hillslopes and valley floors, hypothetically leading to increased storm runoff, more erosive floods, and channel entrenchment (Bailey, 1935; Antevs, 1952). The construction of roads, irrigation ditches, and other floodplain modifications have also been cited as potential anthropogenic influences on arroyo formation (Cooke and Reeves, 1976; Webb, 1985). However, infilled palearroyos exposed in the walls of modern cutbanks indicate that there have been several cycles of alluviation and erosion prior to the influence of Anglo setters (Bryan, 1925; Peterson, 1950). Though attribution of incision to anthropogenic forcings persisted in the literature for many decades, it is now recognized that human activity alone cannot explain all Holocene arroyo cut-and-fill cycles (Cooke and Reeves, 1976).

2.2.2. Climatic

Decades of stratigraphic and geochronologic study in the southwestern U.S. have revealed broad regional correlations in the timing of stream aggradation and degradation in the late Holocene (Haynes, 1968; Knox, 1983; Karlstrom, 1988; Hereford, 2002). These correlations have motivated research into the hydroclimatic changes that could explain the regionally synchronous stream
behavior during these cycles. At least four episodes representing two cycles over the past millennium have been correlated across several catchments in Arizona, New Mexico, and Utah: (1) a period of aggradation before ~1200 AD coincident with the rise of Puebloan cultures; (2) prehistoric arroyo cutting around ~1200 AD that coincides roughly with the Puebloan abandonment; (3) an episode of aggradation from ~1300–1880 AD and (4) historic arroyo cutting from ~1880–1920 AD (Hack, 1942; Haynes, 1968; Hall, 1977; Euler et al., 1979; Graf, 1987; Hereford, 2002; Huckleberry and Duff, 2008) (Fig. 2A). Incipient refilling of the historic arroyos began around 1940 AD in many southwestern streams (Leopold, 1976; Hall, 1977; Hereford, 1984, 1986; Graf et al., 1991). Though several episodes of arroyo cutting and filling prior to 1200 AD have been recognized (e.g. Waters and Haynes, 2001; Mann and Meltzer, 2007; Harvey et al., in press), records of these older events are more rare and generally lack the temporal resolution necessary for inter-drainage comparison.

Mechanisms linking decadal- to centennial-scale climate changes to arroyo cut-and-fill cycles have long been debated. Some early workers speculated that arroyo formation was simply associated with episodes of enhanced precipitation and a resulting increase in runoff (Dutton, 1882; Huntington, 1914; Gregory and Moore, 1931). Bryan (1925) and Hack (1942) suggested as an alternative that it was a change to more arid conditions that increased surface runoff by decreasing vegetation cover on hillslopes. In more recent decades, the increasing density of meteorological and streamflow data has fed a number of studies that attempt to link decadal-scale changes in precipitation frequency and intensity to floodplain growth in modern arroyos. Hereford (1984, 1986), Balling and Wells (1990), and Graf et al. (1991) each used such records to show that the arroyo refilling of the mid-twentieth century generally took place during a time of drought and reduced streamflow. This is in contrast to the historic arroyo cutting of the preceding few decades, which was characterized by more intense precipitation interspersed with drought (Hereford and Webb, 1992).

In addition to a changing hydrology, some have pointed to changes in sediment supply from hillslopes and upper fluvial systems as a primary driver of channel change. Graf (1987) studied the patterns of sediment storage and evacuation for streams of varying drainage area in the Colorado Plateau. He concluded that the storage and transport of sediment are most sensitive to climatic

**Fig. 2.** Climatic and stratigraphic reconstructions for the southwestern U.S.: (A) Late Holocene arroyo cycles in the Colorado Plateau (generalized from Hereford, 2002); (B) Frequency of dated paleoflood slackwater deposits in the southwestern U.S. (redrawn from Ely, 1997 – note abbreviated height of last column); (C) Percent of western U.S. area in drought as derived from tree-rings (black line, smoothed over 60 yr). Two-tailed 95% bootstrap confidence intervals shown as dashed lines, mean percent area shown as gray line (redrawn from Cook et al., 2004); (D) Columns: Frequency of El Niño events per 100-yr bin (modified from Moy et al., 2002). Line: Reconstructed Southern Oscillation Index (data from Stahle et al., 1998); and (E) Cumulative probability density functions for radiocarbon-dated deposits in alluvial (dashed) and bedrock (solid) river reaches (redrawn from Harden et al., 2010).
and land use changes in local, lower-order streams (drainage areas of 10^3–10^4 km²), whereas regional, higher-order streams (10^3–10^4 km²) store and evacuate sediment in response to the changing supply from these smaller local tributaries. This suggests that sediment storage propagates down-system from local streams toward regional streams over time, a finding supported by more recent work in the Great Plains by Mandel (2008). This pattern should be discernable chronostratigraphically as an inverse correlation in sediment age between upper alluvial valleys and down-stream reaches.

Hereford (2002) suggested that the cooler, wetter climate of the Little Ice Age increased freeze-thaw action on hillslopes, thereby increasing sediment yield and promoting regional channel aggradation. A different link between hillslopes and valley floor alluviation is described by McAuliffe et al. (2006), who argue that major hillslope-stripping events have occurred during transitions from drought to episodes of increased precipitation. Further, Graf (1987), Graf et al. (1991), and Pederson (2000) concluded that sediment storage and mobilization within upper fluvial systems is a key process effecting downstream changes in sediment load. Thus, there is broad agreement that late Holocene cut-and-fill cycles likely involve changes in both hydrology and upstream sediment delivery.

2.2.3. Autogenic

Other workers have emphasized the role of autogenic adjustments in driving cycles of aggradation and erosion. They document field examples and experimental studies wherein pulses of incision followed by widening and alluviation migrate up-network in response to the formation of local slope anomalies (Schumm and Hadley, 1957; Schumm and Parker, 1973; Patton and Schumm, 1981). These anomalies represent local base level changes that do not necessarily occur simultaneously across regional catchments. For example, local oversteepening may result from deposition of a tributary debris fan or deposition resulting from downstream losses in sediment transport capacity due to bed infiltration. The resulting oversteepened reaches are subject to higher shear stresses and bed incision during large floods, sending upstream transient waves of incision followed by widening and renewed alluviation. The signature of such internal complex response is a sequence of relatively small-scale, time-transgressive (younging upstream) terraces (Schumm and Parker, 1973; Daniels, 2008). Waters (1985) concluded that such “intrabasin geomorphic parameters” were stronger influences than external climatic drivers on the timing of alluviation and erosion for a network of streams in southeastern Arizona. In a different example of internal response, Patton and Boison (1986) showed that recent landslidel-generated debris overwhelms the fluvial system of Harris Wash, a tributary of the Escalante River in southern Utah, causing the spatial and temporal patterns of alluviation and incision to differ from that seen in other regional streams. Despite these scattered cases, complex response is unlikely to outweigh other allogenic forcings such as climate and land use over late Holocene timescales in the southwest U.S. (Daniels, 2008).

2.2.4. Working hypothesis

Though there may be no simple “smoking gun” to explain all late Holocene arroyo cutting and filling cycles (Cookie and Reeves, 1976), there has been a recent convergence of hypotheses in the literature. Many authors now agree that a shift toward an episode of increased flood frequency was an important factor in prehistoric and historic arroyo cutting (Webb, 1985; Webb et al., 1991; Hereford, 2002; Mann and Meltzer, 2007; Huckleberry and Duff, 2008). Others point out that the effect of such a shift would be enhanced if the watershed were already in a sensitive state due to extended drought and/or land-use changes (Cookie and Reeves, 1976; Webb et al., 1991; Miller and Kochel, 1999; Tucker et al., 2006). There is less agreement on what specific climate shifts could have altered hydrology in such a way as to cause synchronous incision of arroyos over such a large region. For a more detailed treatment of that issue, we point the reader to Webb (1985).

As reviewed by Hereford (2002), many streams in the Colorado Plateau region saw peak streamflow around the time of historic arroyo cutting. These observations are based on tree-ring derived streamflow reconstructions (Hereford et al., 1996a), anecdotal evidence, and in some cases, discharge reconstructions based on flood-stage indicators. While this supports the working hypothesis, performing a similar comparison of paleoclimatological and paleohydrological proxies with prehistoric arroyo cutting is more difficult for several reasons. First is the rough temporal resolution of climatic reconstructions covering the late Holocene (Fig. 2). Tree-ring reconstructions are helpful in that they generally capture variations in cool-season precipitation at an annual resolution. However, their utility is limited by their insensitivity to precipitation intensity, which is arguably more important for flood production. Further, large, destructive floods can occur during extended droughts without affecting tree-ring growth, just as mean precipitation do not necessarily require anomalously large floods (Pederson, 2000; Huckleberry and Duff, 2008).

The types of storms that produce extreme floods in the southwestern U.S. include localized, diurnal thunderstorms associated with the summer monsoon; dissipating eastern Pacific tropical cyclones; and slow-moving winter and spring frontal systems (Ely, 1997). A general rule is that drainages are most responsive to storms of a spatial scale similar to the size of the drainage basin (Leopold, 1942). Therefore, monsoonal storms are more likely to dominate flood hydrology in smaller headwater drainages, while larger frontal systems and tropical cyclones are more likely to trigger large floods in higher-order trunk drainages (Baker, 1977; Graf, 1983; Webb, 1985).

Many workers have cited a centennial- to millennial-scale cycle in the frequency of El Niño-Southern Oscillation (ENSO) events as a potential driver of changes in the frequency and intensity of larger fall and winter cyclonic storm systems in the southwestern U.S. (Hereford and Webb, 1992; Ely, 1997; House and Hirschboeck, 1997; Waters and Haynes, 2001; Hereford, 2002). In addition to causing floods enhanced by saturated soils, these storms are also responsible for much of the winter snowpack that accumulates in higher-elevation drainages (Cayan et al., 1999). Further, Webb and Betancourt (1992) argue that El Niño years are related to more frequent landfall of tropical cyclones from the eastern Pacific, which have been known to produce floods-of-record in drainages in the southwestern U.S. (Webb, 1985). While historic arroyo cutting appears to be coincident with an episode of increased El Niño activity (Fig. 2B and Hereford, 2002), it is difficult to reconstruct the record of earlier El Niño events at a resolution high enough to confirm whether or not prehistoric arroyo cutting can be related to anomalous ENSO behavior (Fig. 2C).

Recognizing the extreme precipitation intensities that occur during late summer convective thunderstorms, Mann and Meltzer (2007) tie their reconstructed histories of aggradation and incision in New Mexico to changes in the strength of the North American monsoon. In contrast to prehistoric variations in cool-season precipitation, which can be reconstructed with tree-rings; short-duration, high-intensity monsoonal storms are very difficult to reconstruct.

Limitations in length and resolution of existing paleoclimatic reconstructions preclude confident determination of the drivers of non-stationarity of large floods. Regardless, one could test the hypothesis that arroyo cut-and-fill cycles are driven by variations in...
the frequency and magnitude of flood-producing storms by comparing dated cut-and-fill cycles with historic and prehistoric flood records from the same drainages (Webb, 1985; Webb et al., 1991; Ely et al., 1996; Hereford, 1999).

3. Paleoflood hydrology

3.1. Background

The field of paleoflood hydrology is based on using depositional and erosional evidence to reconstruct floods that occurred before the instrumented record (Patton et al., 1979; Kochel and Baker, 1982). Like for arroyo cycles, there are existing reviews of paleoflood hydrology (Costa, 1987; Baker et al., 2002; Benito and Thorndycraft, 2005; Baker, 2008). Early paleoflood studies were focused on characterizing catastrophic flood events such as glacial outburst floods (Dana, 1882; Bretz, 1923). Modern applications of these methods began in earnest in the late 1970s, and include extending the flood record to refine flood recurrence intervals (e.g. Baker, 1977; Kochel and Baker, 1982; O’Connor et al., 1994) and paleoflood reconstructions related to climatic trends (e.g. Ely, 1997; Harden et al., 2010). Depositional evidence for paleofloods includes slackwater sediments, perched woody debris, and silt lines plastered on bedrock walls. Erosional evidence includes scarring on trees within the flood zone, abrasion of bedrock walls, and truncation of landforms such as debris fans.

3.2. Application in bedrock canyons

In the Southwest, paleoflood studies rely heavily on slackwater sediments preserved in bedrock canyons. These sand and silt deposits rapidly fall out of suspension in areas of flow separation such as alcoves, backwaters upstream of severe constrictions, and interior channel bends. Repeated deposition in these zones by progressively larger floods produces series of distinct flood deposits, constituting a paleoflood package (Baker et al., 1983; Kochel and Baker, 1988; Benito, 2003; Benito and Thorndycraft, 2005). The stratigraphy of these packages can then be described and dated using some combination of radiocarbon, optically stimulated luminescence, short-lived isotopes, association with cultural materials, and dendrochronology. Workers are often interested in determining the discharge of specific paleofloods, for which they rely on careful identification and surveying of paleostage indicators such as silt lines and slackwater deposit surfaces. Water-surface profiles reconstructed from these stage indicators are then input into a hydraulic modeling package such as HEC-RAS to estimate paleoflood discharges (e.g. Webb and Jarrett, 2002). Approaches utilizing the above methods have produced paleoflood records for dozens of rivers worldwide; each constructed with the goal of better assessing the magnitudes of floods a stream is capable of producing as well as their non-stationarity in recent millennia.

A critical factor in the calculation of paleodischarges is knowledge of channel geometry at the time of deposition (Patton et al., 1979). Most workers make the assumption that the modern channel geometry is a reasonable approximation (Baker et al., 1983; Webb et al., 1991). This assumption would certainly be invalid in those stream reaches undergoing arroyo cutting and filling cycles, where grade changes on the order of 10 s of meters in decades have been recorded. Only a few researchers have attempted to correct for changes in stream grade and/or channel geometry since deposition using geologic evidence (e.g. Webb et al., 2002). Indeed, minimizing this uncertainty is one reason paleoflood hydrologists have focused their efforts on constricted bedrock canyons with relatively stable lateral channel boundaries. However, the thickness of the alluvial veneer is rarely known, and some have noted the possibility of episodic channel aggradation and sediment storage in bedrock canyons during the late Holocene (e.g. Tinkler and Wohl, 1998; Webb et al., 2002; Harvey et al., in press).

3.3. Non-stationarity of dated flood deposits

The southwestern U.S. benefits from an abundance of intact slackwater deposits in bedrock canyons, resulting in a large body of work on paleoflood frequency and magnitude. Regional compilations of this work suggest large floods tend to cluster into particular episodes during the Holocene (Ely, 1997; Harden et al., 2010; Fig. 2B, E). These workers have interpreted this record to suggest that episodes of increased flood frequency generally occur during cooler, wetter periods such as the Little Ice Age (~1500–1900 AD). In contrast, overall drier and warmer episodes like the preceding Medieval Warm Period (~1100–1400 AD) are poorly represented in the flood record. Ely (1997) suggested that these centennial-scale climatic variations are related to shifts in the frequency of El Niño events, which have been statistically linked to cooler, wetter conditions in the U.S. Southwest (Cayan et al., 1999). However, dependable millennial-scale El Niño reconstructions remain elusive, and this proposed correlation is not yet tested. In fact, local paleoflood records for several rivers in the Colorado Plateau argue instead that the LIA was not characterized by frequent, large floods (Webb, 1985; Webb et al., 1991; Webb and Jarrett, 2002).

Indeed, the source of non-stationarity in regional flood frequency records is not simple or clear. In addition to any primary climate drivers, preservation bias and resolution issues obscure the record. Regarding preservation, there is a significant skew toward younger ages that is difficult to de-trend. Harden et al.’s (2010) analysis includes streams ranging from the large trunk drainage of the Colorado River that heads in the Rocky Mountains to lower-order streams of the Colorado Plateau, to streams that flow primarily through the Sonoran desert in southern Arizona, to streams in southwest Texas. Such a blending of drainage locations, sizes, and hypsometries can be problematic for two reasons: (1) The effectiveness of any given storm at producing a flood is dependent on drainage area. Smaller drainages may experience their flood-of-record during localized monsoonal thunderstorms, while the same storm may have little or no geomorphic effect on a trunk drainage downstream (Graf, 1983; Knox, 1983). The inverse is also possible for broader regional storms such as stalled winter frontal systems (House and Hirschboeck, 1997). (2) Climate changes that could control the frequency of large floods may be manifest differently.

Table 1

Examples of drainages featuring both arroyo cycle and paleoflood hydrology research in the southwestern U.S.

<table>
<thead>
<tr>
<th>Drainage</th>
<th>Alluvial cycles</th>
<th>Paleoflood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buckskin Wash, UT/AZ</td>
<td>Hereford (2002); Harvey et al. (in press)</td>
<td>Ely (1992); Harvey et al. (in press)</td>
</tr>
<tr>
<td>San Juan River, NM/UT</td>
<td>Hereford et al. (1996a)</td>
<td>Ely (1992); Enzel et al. (1994)</td>
</tr>
<tr>
<td>Virgin River, UT</td>
<td>Hereford et al. (1996b)</td>
<td>O’Connor et al. (1994)</td>
</tr>
</tbody>
</table>
across physiographic provinces. For example, streams draining the uplands of the Colorado Plateau would likely respond differently to an increase in winter snowpack than streams in the low deserts of southern Arizona. Though these complications make them difficult to interpret, such regional reconstructions suggest that flood frequency and magnitude have seen dramatic variability in the Holocene.

4. Exploring the disconnect between paradigms

4.1. Introduction

Though the study of arroyo cut-and-fill histories and the construction of paleoflood chronologies generally have been separate lines of inquiry, they are inherently related. Both rely upon the analysis and dating of Holocene alluvial deposits. Additionally, since many dryland streams flow for only short periods following storm events, the study of dryland alluvial deposits is in most cases the study of flood deposits (Graf, 1983; Tooth, 2000). Herein lies an important distinction — paleoflood hydrology focuses on large, unusual floods, whereas arroyo stratigraphies may be composed of deposits from any range of flow magnitudes. Finally, the two approaches have been applied in neighboring or even the same reaches of a single drainage without much regard to the other. The following discussion reviews some of these cases, as well as previous attempts to link the two record types from the scale of a single watershed to the entire southwestern U.S.

4.2. Settings between end-members

There are many drainages that contain both end-member valley geometries shown in Fig. 1. In some cases the transition between them is abrupt and obvious, while in others it is more gradual and diffuse. These more ambiguous, transitional reaches present a challenge, as it may not be clear whether perched alluvial deposits therein were emplaced by large floods or are remnants from an episode of aggradation. At what point in such a transition zone do the cycles of aggradation and degradation that characterize alluvial reaches give way to a stable canyon reach that preserves only larger floods? It is possible that hydrologic modeling could help define the geometric transition between these two end-member reach types.

The Colorado River is a classic example of a drainage that features varying valley geometries along its length, as well as deposits that have been interpreted as both paleoflood archives and fill terraces. O’Connor et al. (1994) interpreted a sequence of deposits at Axehandle Alcove in Marble Canyon as a sequence of paleoflood deposits interbedded with locally-derived sediment and cultural material. They use the surface of the deposits as paleostage indicators to calculate discharges, assuming that the channel geometry in 1990 AD reflects the geometry at the time of emplacement. They acknowledge that this assumption is their largest source of uncertainty, and suggest that their reconstructed discharges should be interpreted as minima due to probable channel scour during floods. They do not, however address the possibility of longer-term grade changes over the >4000 yr-long record.

Representing the cut-and-fill approach, Hereford et al. (1996b) studied the debris fans and alluvial terraces that line the Colorado River at Nankoweap Rapids, ~80 km downstream from the site studied by O’Connor et al. (1994). They interpreted alluvial deposits 5–17 m above the modern river as a series of three inset aggradational terraces deposited between ~800 BC and 1880 AD. They associate deposition of the alluvial terraces with changes in the grade of the river related to increased activity on nearby debris fans. Interestingly, the dated alluvial sequences appear to correlate to the aggradational sequences described elsewhere in the Colorado Plateau (Hereford, 2002). In a more recent study aimed at addressing the confusion surrounding alluvial deposits along the Colorado River, Tainer (2010) showed that Holocene alluvial deposits in (constricted) Glen Canyon include strong evidence for both changes in river grade as well as more recent paleoflood deposits. This result suggests that despite the narrowness of the canyon at the study site, bed aggradation and degradation has taken place in recent millennia.

Clearly, the interpretations of the alluvial record in Grand Canyon by Hereford et al. (1996b) and Tainer (2010) are remarkably different than that of O’Connor et al. (1994). Considering the overlapping ages and landscape positions of the studied deposits, it is possible that the paleoflood sequence studied by O’Connor et al. (1994) was a vertical cross-section through one or more of the alluvial terraces described by Hereford et al. (1996b) and Tainer (2010). Alternatively, the suite of inset fill terraces described by Hereford et al. (1996b) could be flood packages formed while the river underwent overall lowering of grade. A third solution is that both approaches are valid, and terrace formation is associated with localized aggradation around tributary debris fans. In any case, the Colorado River is an example where it is not always clear whether the Holocene alluvium should be interpreted as a stack of paleoflood deposits or as the result of a more complicated sequence of changes in channel grade. We suggest that such ambiguous reaches may be as common as those that are clearly recognizable as belonging to either end-member stream geometry.

4.3. Unreconciled results from both approaches in single drainage

There are several examples where both approaches have been demonstrated on different geomorphic reaches of the same streams. In fact, a series of these cases in the southern Colorado Plateau was the subject of an AMQUA field trip in 1996 (Ely et al., 1996). Field trip participants visited several locations where the alluvial deposits of both alluvial and constricted reaches had been studied through separate lines of inquiry. For example, the Paria River in southern Utah has been the subject of both upstream arroyo stratigraphy (Hereford, 1986, 2002) and downstream paleoflood research (Ely, 1992; Webb et al., 2002). Additional examples exist throughout the Southwest (Table 1), yet little work has been done to reconcile these results and their distinct interpretations regarding channel processes and controls. In most cases, such reconciliation is precluded by inadequate temporal resolution, yet workers sometimes do not acknowledge the results and implications of the alternative approach.

A worthwhile exercise for the cases mentioned in Table 1 would be to compile and compare the chronostratigraphic results from both approaches on a stream-by-stream basis, highlight the data gaps that currently inhibit direct comparison, and attempt to fill those gaps using all available techniques. The working hypothesis described above in Section 2.2.4 and originally described by Hereford (1999) predicts that, in a given drainage, the ages of arroyo-fill deposits should be inversely correlated with paleoflood deposits.
slackwater deposits (Fig. 3). As an example, in the alluvial reaches of the Paria River basin, Hereford (1986, 2002) identified two major arroyo-cutting events centered around 1300 AD and 1880 AD, each bounded by longer-lasting aggradational episodes. Downstream, in the narrows of Paria Canyon, Webb et al. (2002) identified 11 slackwater flood deposits. The highest deposit surface was determined to be historic (pre-1955 AD), and was linked to one of the largest known historical floods (either in 1862, 1884, or 1909 AD). The next highest deposits date to around 1420 AD and 1280 AD, respectively. Thus, these highest three flood deposits appear to be broadly correlated with upstream incision events, though the link is not strong. Webb et al. (2002) also noted that several large historic floods were not represented in the alluvial record of the bedrock canyon at all. As with most of the other cases from Table 1, more detailed, higher-resolution age control must be produced before reconciliation of the records in the two end-member settings of the Paria River is possible.

4.4. Regional-scale comparisons

Direct comparison of regional paleoflood compilations with the record of arroyo dynamics is difficult, in part due to the contrasting temporal resolution between them and uncertainties associated with radiocarbon-based age control (Ely et al., 1996; Hereford, 2002; Huckleberry and Duff, 2008) (Fig. 4). Arroyo cut-and-fill records are more numerous and supported by a close association with archaeological studies, radiocarbon ages, and dendrochronology. The paleoflood record, on the other hand, is limited to a smaller dataset. Additionally, the regional flood chronology constructed by Ely (1997) bins large flood events into 200-year intervals (Fig. 2B). We know, however, that arroyo headcuts can pass through a drainage in a matter of a few years to decades (Gregory and Moore, 1931; Webb, 1985). If the hydroclimatic conditions associated with arroyo cutting occur over only years to decades, they could be lost in 200-yr bins.

A newer method of synthesizing Holocene alluvial records over entire regions at higher resolutions has been developed in recent years (e.g. Macklin and Lewin, 2003; Lewin et al., 2005; Thordycraft and Benito, 2006; Benito et al., 2008; Harden et al., 2010). Focused mainly on rivers throughout Europe, these studies involve the construction of large databases of dated alluvial deposits across regions. They first classify the dated units based on their geomorphic and stratigraphic contexts. For example, Thordycraft and Benito (2006) break their dated deposits into the following settings: alluvial overbank, flood basin, alluvial channel, fluvi-torrential, and slackwater flood deposits, before converting them into cumulative probability distribution functions (CPDFs) and comparing them across geomorphic contexts and over time.
Studies of this type have the potential to reveal the broader adjustments of fluvial systems to anthropogenic and climate forcings over the mid-late Holocene as a function of geomorphic setting.

Harden et al. (2010) builds upon Ely’s (1997) record by applying this methodology to the abundant dated deposits in the southwestern U.S. They compiled a database of 724 radiocarbon dates from 37 locations, making the important step of distinguishing between “bedrock” and “alluvial” geomorphic settings. From this database, they constructed CPDFs for alluvial deposits found in either setting. The temporal pattern of these data illustrates a rough inverse correlation between deposits in the two reach types, at least toward the latter part of the record (Fig. 2E). Such a pattern would appear to support the hypothesis that episodes of increased flood frequency are associated with regional arroyo-cutting events. Harden et al. (2010) suggest that alluvial reaches may not capture the largest floods due to channel scour and enlargement during such events. Alternatively, the more stable channel boundaries in the bedrock reaches allow for more complete preservation of larger floods (Baker, 1977). They conclude that episodes of frequent, large floods as preserved in bedrock reaches correlate with cooler, wetter periods; whereas flood deposits are more likely to be preserved in alluvial reaches during cool, dry periods.

For the purposes of reconciling the temporal relations between the two main types of dryland alluvial records, the Harden et al. (2010) study is subject to the limitations described earlier in section 3.3. Those issues could be addressed by comparing only streams of a similar drainage area and physiography. Another element of uncertainty associated with this method is the challenge of distinguishing between climatically significant flood deposits and those that record minor, less significant events. Since paleo-flood magnitudes are calculated using flood-stage indicators, factors that influence the apparent stage of a paleoflood such as syn- or post-depositional incision or aggradation can have a dramatic effect on resulting interpretations.

The preservation potential of a fluvial deposit is intricately tied to the particular process and geometry in the reach of interest (Lewin and Macklin, 2003). As an example, in the case of a channel that spends hundreds of years migrating laterally across an alluvial valley at a steady grade, most flow events will not be preserved. In bedrock canyons, deposits are likely to be preserved only if a flood event is large enough to passively overtop existing deposits in a sheltered zone, yet is small enough not to scour out the entire package. Effectively, however, a greater range of flow events is likely to be preserved in alluvial reaches, due to overall increased accommodation space along the drainage.

Despite existing limitations and uncertainties, regional paleoflood compilations can provide a helpful context in which to view late Holocene arroyo cycles, especially once they begin to include paleoflood deposits whose ages are constrained by other dating techniques such as OSL, dendrochronology, and short-lived isotopes.

4.5. Single-drainage comparisons

Few workers have addressed the chronostratigraphic relation between record types in a single drainage. For his doctoral dissertation, Webb (1985) attempted to directly reconcile alluvial records from both broad and constricted valley geometries within the Escalante River drainage of south-central Utah. The Escalante has a pattern common to the Colorado Plateau, consisting of an upstream reach with an arroyo cut into a broad valley fill and a downstream reach that is significantly constricted by bedrock walls. Webb studied deposits in the upper alluvial reach to reconstruct its arroyo cut-and-fill history and in the constricted reach to develop a paleoflood chronology, constraining ages of deposits with radiocarbon dating, the instrumented record, and historic photographs. He identified three episodes of arroyo formation: ~900 AD, 1600 AD, and ~1900 AD. The most recent event could be traced to a large flood observed by settlers that caused a knickpoint to migrate several kilometers upstream. He notes the rough correlation between clusters of large floods between 1200–900 yr BP and 600–400 yr BP with the development of the first and second paleoarroyos, respectively, although this link is limited by uncertainty in radiocarbon analysis.

Working on Harris Wash, a tributary in the Escalante River basin, Patton and Boison (1986) similarly identified sandy flood deposits that they temporally correlated with incision of valley-fills upstream. They noted that the flood deposits they linked to upstream incision were generally best-preserved in areas of flow separation near bedrock walls, yet, the sedimentological characteristics that distinguish these deposits from the alluvial-valley fills which they overlie were not described in detail. They suggest that further identification and dating of these incision-related flood packages could help refine the complex alluvial history of the region.

Another interesting case is that of Kanab Creek, one of the deepest and most dramatic arroyos in the Colorado Plateau. By examining anecdotal evidence and flood-scarred trees, Webb et al. (1991) document that the modern arroyo was cut by a series of exceptionally large floods beginning the late 19th century. Despite the magnitude of channel change caused by floods in the upper alluvial reach, re-photography of several historical photos suggests that there was very little channel scour or fill in the downstream bedrock canyon. Though Smith (1990) and Summa (2009) have investigated earlier arroyo cycles in Kanab Creek, contemporary flood deposits have not been identified in the canyon downstream.

Following the lead of Webb (1985) and Webb et al. (1991), Harvey et al. (in press) performed a similar study along Buckskin Wash, a tributary to the Paria River in the Colorado Plateau that features an alluvial reach draining into a slot canyon. They identify four episodes of arroyo formation since ~3 ka, with the last two occurring at ~1300 AD and ~1880 AD (Fig. 4). The majority of the slakewater deposits in the slot canyon downstream were deposited between ~1850 and 1950 AD, suggesting that the bedrock canyon may record the same floods that caused arroyo cutting upstream. However, noting the complete absence of deposits from ~1000 AD to ~1850 AD in the slot canyon, Harvey et al. argue that preservation of flood deposits in the slot canyon was temporarily enhanced by extreme sediment loading resulting from the incision of upstream valley-fills. This phenomenon would serve to exaggerate the frequency and magnitude of floods during arroyo cutting and underestimate those that occurred during upstream aggradation. This has important implications for paleoflood studies, as the site in Buckskin Wash has been referred to as a classic locality for slakewater deposits in the southwest U.S. (Ely et al., 1996; Knox, 2000).

5. Reconciliation

The studies summarized above are examples of how alluvial records have been used to reconstruct the late Holocene behavior of streams in the southwestern U.S. They also set the context for the questions that remain in order to reconcile the different approaches. Are constricted-reach channels truly stable over Holocene time while neighboring alluvial reaches experience bed elevation changes of tens of meters? How do alluvial records (and assumed stream behaviors) geometrically transition from one record type to the other along a single drainage? What are the effects in both reach types of the largest floods vs. smaller, more frequent events? Can we define the hydraulic and geometric
transition or threshold between record types and clarify their distinctions?

We suggest that resolving these issues will require a series of focused chronostratigraphic studies like Webb’s (1985) and Harvey et al.’s (in press), wherein records from both end-member reach types are studied and compared in detail within a single drainage. Attention must also be paid to the transitional reaches that separate end-members. In order to achieve the precise, high-resolution age control necessary to compare the temporal pattern of deposition, a suite of geochronologic methods must be employed. Newer tools like optically-stimulated luminescence and short-lived isotopes can augment AMS radiocarbon, dendrochronological, and archeological methods; especially where datable organic or cultural material is absent.

Equally important, more sedimentological detail is needed to achieve a process-based understanding of deposition across the two major reach types. There is a notable lack of such data in the literature. For example, one can use the sedimentology of flood deposits in bedrock canyons to distinguish between the scenarios shown in Fig. 3. Typical slackwater deposits consist of silt- and sand-size particles that fall rapidly out of suspension in areas of low flow velocity. If coarser material and bedforms that resemble the high-velocity channel bed are preserved high in outcrop, it is likely that significant changes in bed elevation have occurred. Further, analyses of flood deposit composition and grain size distributions could be helpful in correlating flood packages over many kilometers, allowing exploration of the control of valley geometry on flood deposit preservation.

Thanks to advances in hydraulic modeling techniques, exploitation of the role that valley geometry plays in controlling long-term stream behavior in constricted vs. alluvial reaches is becoming increasingly possible. New generations of two-dimensional modeling packages may be better able to capture the complex boundary conditions and across-channel variations in velocity or shear stress than existing one-dimensional models (Miller and Cluer, 1998). Such modeling may also allow exploration of the transition zone between end-member geomorphic settings. If we can quantify the thresholds in valley geometry that determine the stability of channel geometry and control the preservation potential of events of various magnitudes, it could help guide those that work in such settings toward the correct interpretation of the alluvial deposits stored therein.

6. Conclusions

There is a notable disconnect between the approaches taken by those studying arroyo cut-and-fill cycles in broad alluvial valleys and those studying paleoflood records in bedrock canyons. While each approach has been demonstrated dozens of times in end-member settings, little effort has been made to relate the two record types in a given drainage. Similarly, little attention has been paid to those reaches that lie morphometrically between the two end-member geomorphic settings. However, the two seemingly disparate datasets are fundamentally related in that they rely on the analysis of late Holocene alluvial deposits, and are often undertaken in different parts of the same streams. Further, reconciliation of the two approaches can serve as an important test of the working hypothesis in the arroyo cut-and-fill literature; that arroyos are cut during episodes of unusually frequent, large floods tied to external climatic phenomena.

As these datasets continue to grow and new tools are employed, it is becoming possible to combine them into a greater model of fluvial response to environmental change in drylands. Regional syntheses must be complemented by more focused, watershed-scale studies. Every geochronological tool available must be embraced in order to achieve sufficient temporal resolution to compare records both along and across drainages. The value of such studies would also benefit from greater sedimentological analysis of alluvial deposits in either end-member setting as well as the transitional zone between. Finally, improved numerical modeling capabilities may permit quantitative exploration of the control that reach geometry has on the preservation of alluvial deposits therein. The collective results of these additional studies will help us approach a more complete understanding of how dryland fluvial systems have adjusted to past environmental changes and how they might behave in the future.

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