

# The geomorphic legacy of water and erosion control structures in a semiarid rangeland watershed

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# ESPL

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**ABSTRACT:** Control over water supply and distribution is critical for agriculture in drylands where manipulating surface runoff often serves the dual purpose of erosion control. However, little is known of the geomorphic impacts and legacy effects of rangeland water manipulation infrastructure, especially if not maintained. This study investigated the geomorphic impacts of structures such as earthen berms, water control gates, and stock tanks, in a semiarid rangeland in the southwestern USA that is responding to both regional channel incision that was initiated over a century ago, and a more recent land use change that involved cattle removal and abandonment of structures. The functional condition of remnant structures was inventoried, mapped, and assessed using aerial imagery and lidar data. Headcut initiation, scour, and channel incision associated with compromised lateral channel berms, concrete water control structures, floodplain water spreader berms, and stock tanks were identified as threats to floodplains and associated habitat. Almost half of 27 identified lateral channel berms (48%) have been breached and 15% have experienced lateral scour; 18% of 218 shorter water spreader berms have been breached and 17% have experienced lateral scour. A relatively small number of 117 stock tanks (6%) are identified as structurally compromised based on analysis of aerial imagery, although many currently do not provide consistent water supplies. In some cases, the onset of localized disturbance is recent enough that opportunities for mitigation can be identified to alter the potentially damaging erosion trajectories that are ultimately driven by regional geomorphic instability. Understanding the effects of prior land use and remnant structures on channel and floodplain morphologic condition is critical because both current land management and future land use options are constrained by inherited land use legacy effects. Published 2017. This article is a U.S. Government work and is in the public domain in the USA

**KEYWORDS:** arroyo incision; gully erosion; headcut advance; floodplain runoff; knick zone propagation; human impacts

## Introduction

Agriculture is one of the oldest human influences on earth system processes (Hooke, 2000; Pongratz *et al.*, 2008). Much of the world's grain and livestock are produced in drylands that cover approximately 40% of the globe (Safriel and Adeel, 2005). Across these vast regions, where water availability is limited by both climate and geographic distribution, the success or failure of agricultural operations has been and continues to be fundamentally tied to water development. The ecologic, hydrologic, and geomorphic effects of agricultural water systems ranging from simple runoff collection barriers to extensive networks of water distribution canals can endure for millennia (Monger *et al.*, 2015).

Remnants of rainwater harvesting systems have been found in the Middle East, Asia, Africa, and the Americas (Bruins *et al.*, 1986). Abandoned water harvesting structures dating back 3000–4000 years continue to capture runoff water today in the Negev Desert (Lowdermilk, 1960; Monger *et al.*, 2015),

evidenced by local vegetation that responds to enhanced soil moisture. In the western hemisphere early native inhabitants of Peru and Bolivia constructed terraces and extensive canal systems (Tainter, 1988) to manipulate soil and water. In southern Mexico's Tehuacán Valley 2500 years ago, inhabitants constructed the largest known prehistoric water management system in the New World with canals, secondary canals, and feeder ditches extending more than 1200 km (Caran and Neely, 2006). These systems have long lasting geomorphic influences on the surrounding landscape. Through the depositional processes of sedimentation and mineralization the canals became elevated thus altering topography, disrupting overland flow paths, and promoting sediment accumulation (Caran and Neely, 2006). In the deserts of North America, runoff capture and redistribution of surface-water flow through irrigation systems enhanced prehistoric agriculture (Andrews and Bostwick, 2000). These water diversions were constructed over several centuries to irrigate agricultural fields, which resulted in distinct soil textures and chemistry that persists today (Woodson *et al.*,

2015). Surface-water runoff was also captured and retained through the use of rock alignments forming contour terraces and grids that supported prehistoric agave cultivation. These structures persist on the landscape today with recently documented long-term impacts on sediment distribution and soil texture (Doolittle *et al.*, 2004).

Remarkably, many contemporary efforts to control surface runoff in drylands are reinterpretations of the techniques developed in the Middle East and Americas (Fidelibus and Bainbridge, 1995) and are conceptually similar to their ancient counterparts that functioned to capture and spread or divert runoff water to reduce velocities, promote infiltration, and increase soil moisture to support vegetation. As a result of relatively recent advances in the scientific understanding of hydrologic and erosion processes and interdisciplinary watershed management, modern surface-water manipulation practices often serve multiple purposes including erosion control, soil conservation, habitat enhancement, and ecosystem sustainability (Fuhlendorf *et al.*, 2012). Although many agricultural lands have benefited from treatments to enhance sustainability, recent research has pointed to the potential for structural practices that alter water and sediment to actually exacerbate erosion, especially if the structures are not maintained or are abandoned. For example, in Italy, where the tradition of agricultural terracing to control water distribution has been documented since the Middle Ages, current slope failures and landslides associated with terraces abandoned in the mid-1900s have recently been documented, and the threat of accelerated slope erosion currently poses a concern to downslope local communities (Tarolli *et al.*, 2014). Similarly, in China, agricultural terraces that are partially or completely collapsed contribute to land degradation (Schönbrodt-Stitt *et al.*, 2013), and although intended to function as conservation structures, eroded terrace walls in Spain have been shown to enhance gully-lying and erosion (Lesschen *et al.*, 2009).

In contrast to visually striking terraced landscapes, topographic modification associated with water development in rangelands is often less obvious from casual observation. For example, many western United States (US) rangelands are characterized by remote, expansive geographies that encompass mountains adjacent to alluvial-fan lowlands within which the presence of water and erosion control structures, although sometimes quite large, are not readily evident to passersby.

The primary agricultural use of western US rangelands is livestock production (Starrs, 1998). Although livestock were introduced in the 1500s in the southwestern US (Hamilton, 1884), the number of domestic cattle and associated grazing in southern Arizona increased substantially in the late 1800s and early 1900s (Wagoner, 1952) as water resources were developed. Early water development in southern Arizona focused on existing springs and seeps (Hamilton, 1884), and subsequent efforts were directed at improving water distribution to align the distribution of cattle and forage (Bailey *et al.*, 1996). In the 1930s, the newly formed US Soil Conservation Service began engaging in large-scale water improvement projects, often in cost-share arrangements with ranchers, not only to dig or drill wells but also to construct earthen stock tanks, water spreader berms, and long dikes (Helms, 1992) to divert and capture surface-water runoff. These structures enhanced water supply for cattle and vegetation and were often constructed with the dual purpose of mitigating erosion problems.

Although long-term maintenance of soil and water control structures is critical for preventing damage from scour and erosion, thousands of these structures dot the western US landscape in varying states of upkeep (Berg *et al.*, 2016) as a result of many factors including changing land ownership or use, lack of knowledge, or neglect. Overstocking and droughts

during the late 1800s and early 1900s have been widely researched and associated with widespread landscape degradation (Bahre and Shelton, 1996). However, the current geomorphic impacts of structures such as water spreaders and erosion control berms have been overlooked in the literature and the legacy impacts of relatively recent structural control over water and sediment in US rangelands remain largely undocumented. In particular, there is a lack of knowledge of the unintended geomorphic consequences of structures that have been abandoned. What are the impacts of the structures? How important are the legacy impacts for predicting how these landscapes will evolve and what do they mean for future land management? These knowledge gaps are critical because both current land management and future land use options are constrained by inherited land-use legacy effects (Monger *et al.*, 2015).

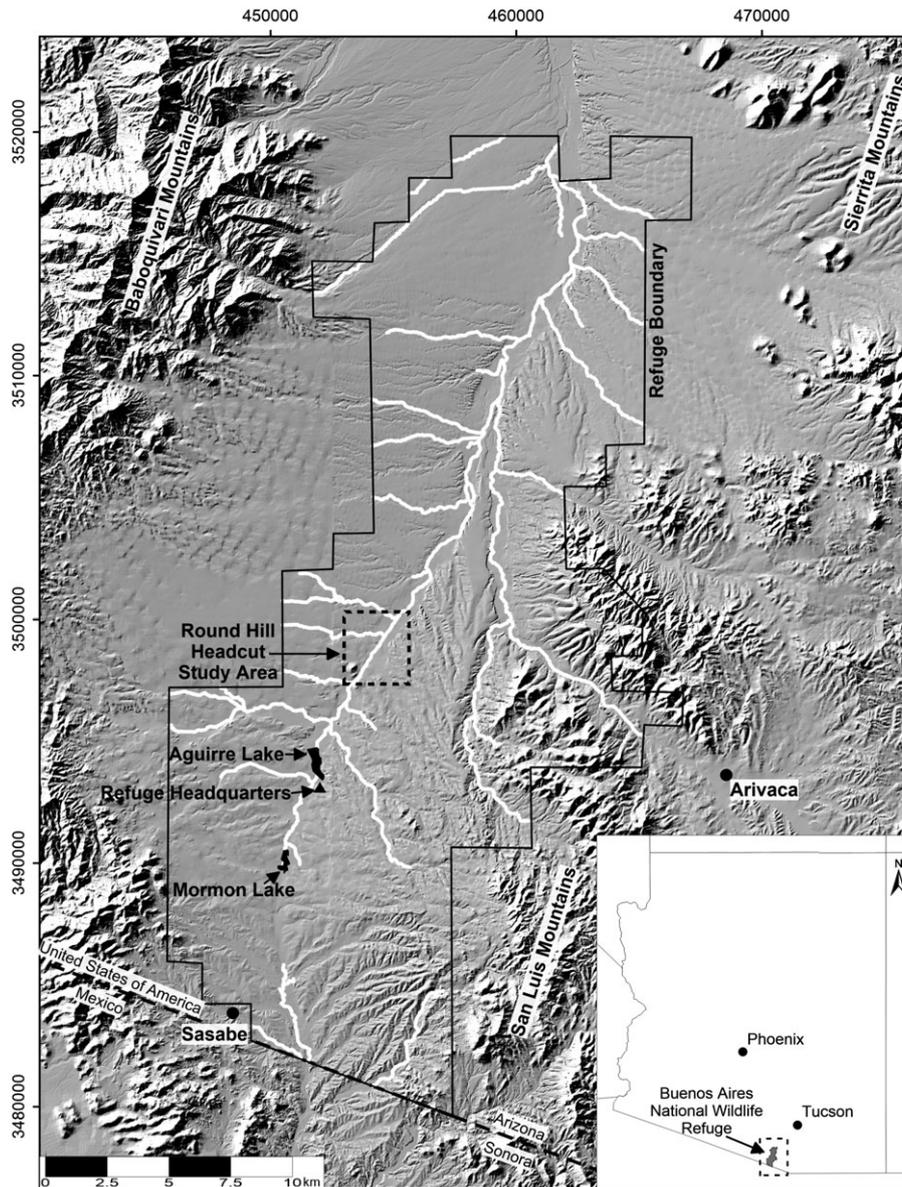
This paper presents a preliminary inventory of legacy surface-water runoff and erosion-control structures in a semi-arid rangeland watershed in southern Arizona, USA that was grazed by cattle for at least a century. Thirty-two years ago, the cattle were removed and the structures were essentially abandoned. Currently, they are posing an erosion threat to a large expanse of grassland. The inventory was based on aerial photography, satellite imagery, airborne lidar data and a remotely sensed assessment of structural condition as first steps in understanding the role of legacy structures on current gully-lying and inchoate geomorphic disturbance. Second, a rapidly eroding headcut site was selected to exemplify and quantitatively assess gully initiation and growth associated with a structurally compromised earthen berm coupled with a concrete water-control structure. This case study is important as it identifies remnant rangeland-management infrastructure as a critical risk to gully-lying and channel incision that is a large-scale threat to soil, water, and habitat resources.

## Methods

### Study site

The inventory and assessment was performed at the Buenos Aires National Wildlife Refuge (BANWR, Figure 1), located in southern Arizona, USA. The BANWR encompasses 47 493 ha within which Sonoran semi-desert grasslands make up 40 470 ha, and elevations range from 950–1150 m. The refuge lies in the Altar Valley, a 72 km long basin located in the western North American Basin and Range Physiographic Province, draining northward from the US–Mexico border. This semi-arid region is characterized by sparse precipitation and a lack of natural surface water. Mean annual precipitation is 415 mm, more than half of which occurs from July–September during the North American Monsoon (Adams and Comrie, 1997). The majority of runoff occurs when intense summer convective thunderstorms generate short-duration flash floods. Mountain slopes are covered with thin stony soils, while the Altar Valley contains deep accumulations of sedimentary fill. Soils in the valley are heterogeneous and consist of mature soils with subsurface clay on older bajada surfaces and less mature soils with higher infiltration capacities on lower, younger surfaces (Bezy *et al.*, 2007; Beaudette and O'Geen, 2009; <https://casoilresource.lawr.ucdavis.edu/gmap/>).

Beginning in the late 1880s, major streams throughout the region incised into Quaternary valley fills and developed into deeply entrenched channels, known locally as arroyos (Cooke and Reeves, 1976). Since then, high-velocity runoff has been concentrated within entrenched channels, forming a feedback loop that promotes further channel incision and bank erosion;



**Figure 1.** US Fish and Wildlife Service Buenos Aires National Wildlife Refuge location map.

however, in the absence of high-magnitude flood flows or where subsequent embankment widening has reduced stream power, some reaches are experiencing localized aggradation. Although the causes of regional cycles of entrenchment are the subject of much discussion (Schumm, 1977; Graf, 1988; Webb and Hereford, 2010; Aby, 2017), it has been hypothesized that failure of the Aguirre Lake dam, built in the 1880s to capture runoff from Lopez and Compartido Washes, was the proximate cause of recent entrenchment of Altar Wash that began in 1905 (Sayre, 2002). Currently, Altar Wash and many of its tributaries are deeply entrenched, and floodplain terraces are hydrologically disconnected from primary channels. Ongoing channel erosion and loss of floodplain vegetation are of concern to local land managers and valley residents.

Since the late 1800s, land use in the Altar Valley has been dominated by commercial ranching. The Buenos Aires Ranch was established at the headwaters, and artificial water development began in the decade of the 1880s. Through a succession of ranch owners, surface-water runoff was systematically altered to accomplish both water storage and what was in effect grass 'farming' of forage that supported cattle operations. Regionally, the practice of manipulating runoff in support of dry-land farming with floodwater is centuries old (Bryan, 1929;

Stewart, 1940), but the extent of runoff manipulation by way of flood gates, long berms (dikes), water spreader berms, and earthen stock ponds to control the flow of water through diversion, conveyance, and storage on the Buenos Aires Ranch was unusually high compared with other locations. Although nominally constructed to supply water to livestock, once completed the dominant impact of these structures was in fact hydrologic.

Operating and maintaining the diversion infrastructure were ongoing tasks requiring consistent on-the-ground attention by ranch managers, which decreased markedly after 1985 when cattle were removed and the US Fish and Wildlife Service established the Buenos Aires National Wildlife Refuge. A comprehensive history of ecology and land ownership, use, and management of this landscape as a private, working cattle ranch and its conversion to the BANWR was published by Sayre (2002). After conversion to the wildlife refuge, maintenance of many of the water-control structures ceased, and management was focused on grassland restoration for wildlife habitat. These management efforts included prescribed burning, revegetation, localized erosion control, and wildlife water development. Today the remnant water and erosion-control structures of prior ranching operations sit largely unattended and generally undocumented, and many have experienced

substantial scour and erosion leading to localized incision and gully. As a result of deferred maintenance, the current dominant impact of many of these structures is geomorphic.

## Types of structures

Water control and distribution, and erosion control, were primarily accomplished through six types of structures described below and summarized in Figure 2. Stock tanks are excavated depressions behind earthen dams that temporarily store surface runoff. Small rangeland dams are often built in series along channels and are sometimes coupled with water harvesting berms that direct intercepted runoff into the excavated tank, and thus affect both runoff water storage and distribution. Stock tanks also retain sediment thereby reducing downstream sediment yields (Nichols, 2006). Water spreaders are linear earthen berms constructed on the contour perpendicular to the land slope to intercept surface runoff water and temporarily store it through soil infiltration. Water spreaders enhance vegetation that responds to increased soil moisture and many were constructed to rehabilitate degraded rangelands (Rango and Havstad, 2011). Long earthen berms (or dikes) were constructed roughly parallel to entrenched channels, sometimes for thousands of meters, to redirect surface runoff away from arroyo banks and gully heads formed through lateral bank erosion, and thus limit further gully head advance. Long berms may incorporate a concrete spillway to route excess runoff without inducing erosion. On the BANWR, control of runoff was also accomplished with drop-board gates constructed at ground level to regulate water delivery further down slope. Drop-board gates consist of vertical iron pilings cast into a concrete spillway, between which boards could be dropped to form a barrier to water flow or divert runoff, thus controlling the distribution. Lastly, in recent decades in-channel rock gabion dams constructed using rock-filled wire baskets were installed in an attempt to mitigate channel erosion by inducing channel deposition and regrading incising channels.

## Structure inventory and assessment

We acquired aerial photographs from 1937, 1956–1958, 1974, 1983 sourced from the Arizona State University map collection and the USGS Earth Explorer website. These images were georeferenced using ArcMap (ArcGIS Desktop [version 10.4], ESRI, Redlands CA). More recent georeferenced imagery from 1992, 1996, 2005, and 2016 were sourced from Google Earth to interpret current conditions.

Structures were identified, digitized, and measured by visually inspecting aerial imagery. Locations of permitted stock tanks were identified using records from the Arizona Department of Water Resources surface water rights database. In addition, breaches (a break through a structure) and flanking (scour around a structure) were visually identified and digitized. Before 2016, the scale and resolution of available imagery was often insufficient to identify smaller water control structures, such as concrete spillways and drop-board gates. Once structures were identified in recent higher-resolution imagery, temporal patterns of associated scour and erosion were assessed using lower-resolution earlier photos at coincident locations. The high resolution of recent imagery presents a clearer picture of the relation between water control structures and landforms. On the ground, it can be difficult to determine the spatial relation and hydrologic connectivity among structures that were often constructed as part of a larger system of water distribution, either contemporaneously or over the course of many decades.

Thus, aerial photography is a critical tool for deciphering the spatial relation of structures.

The advancing headcut of a gully located near Round Hill (Figure 1) was quantified by digitizing the location of the gully head in sequential images. Aerial lidar data (July 9–14, 2016), orthoimagery (June 2016), and Surfer (Golden Software [version 14], Golden, Co) were used to quantify the current volume of evacuated sediment. In addition, field site visits were conducted to verify interpretations and measure dimensions of a subset of the structures.

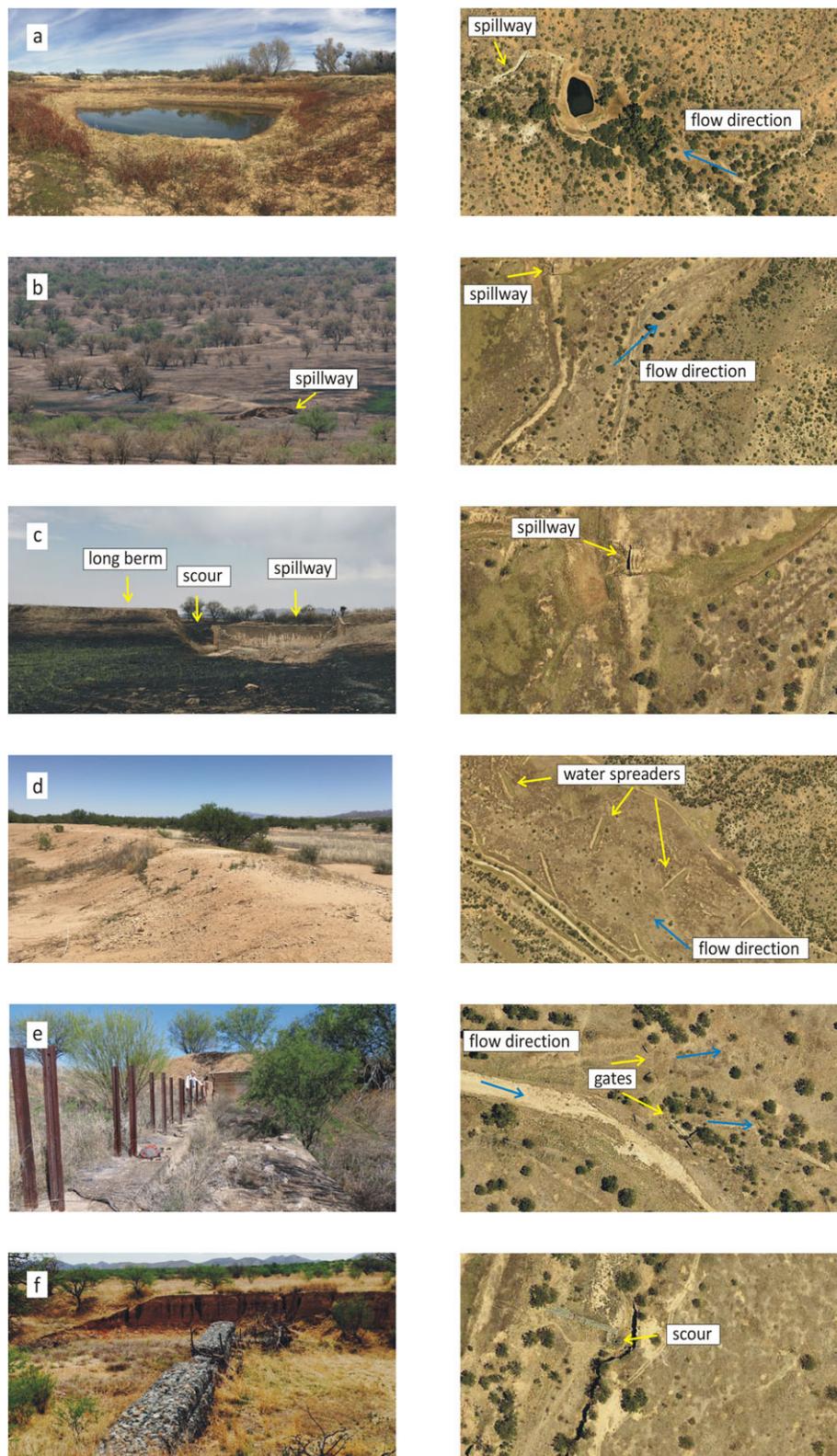
## Results

Twenty-seven long earthen berms, many of which parallel the Altar Wash, 218 shorter earthen water spreader berms, and 117 stock ponds were identified. In addition, 29 concrete water control structures and 3 in-channel dams constructed of rock filled gabion baskets were identified. Only 1% of the structures were constructed after 1985. The general spatial distribution of these structures can be seen in Figure 3, which also shows details of the spatial arrangement of long berms and floodplain water spreader berms in the area of the Round Hill headcut site in relation to dominant streamlines.

Observations from aerial imagery indicate that the incidence of failure among abandoned water-and sediment-control structures is high (Table I). Only 14 of 27 long berms remain intact, while 48% have been breached and 15% have been flanked. A higher proportion (65%) of shorter water-spreader berms on floodplains are intact, however 18% of these structures have been breached and 17% have been flanked. All of the rock-filled gabions structures, which were constructed more recently in the 1990s, have failed and have experienced lateral scour. Concrete water-control structures, such as drop-board gates and concrete spillways, had the lowest failure rate, with 17% breached and 7% flanked. Seven of the 117 (6%) stock tank dams are breached.

Redirection of runoff, channel incision, and lateral headcutting are a few of the impacts that are obvious from aerial photographs, and in many cases the geomorphic responses to breaches and flanking are substantial. To illustrate this point, a specific site located near Round Hill (Figure 1) exemplifies typical conditions and geomorphic responses to structural compromise. Historically, Round Hill stock tank collected floodplain runoff via a long earthen berm that bisects the floodplain south of the tank. A drop board gate (dated 1937 in the concrete wingwall) in the earthen berm diverted runoff either into the stock tank or to lower elevation floodplain regions. Although constructed at ground level, the concrete structure was subsequently undercut by an advancing incision knick zone that originated from the entrenched Puertocito Wash about 500 m to the east (Figure 4). A second long berm located down-slope of the drop-board gate appears to have been constructed to control lateral channel bank erosion and to mitigate headcutting. This berm also terminates at a concrete drop-board gate at its northern end. Although this gate is intact and sits at ground level, the berm was breached in multiple locations and a headcut is advancing through a 17.3 ha floodplain vegetated by native and non-native grasses.

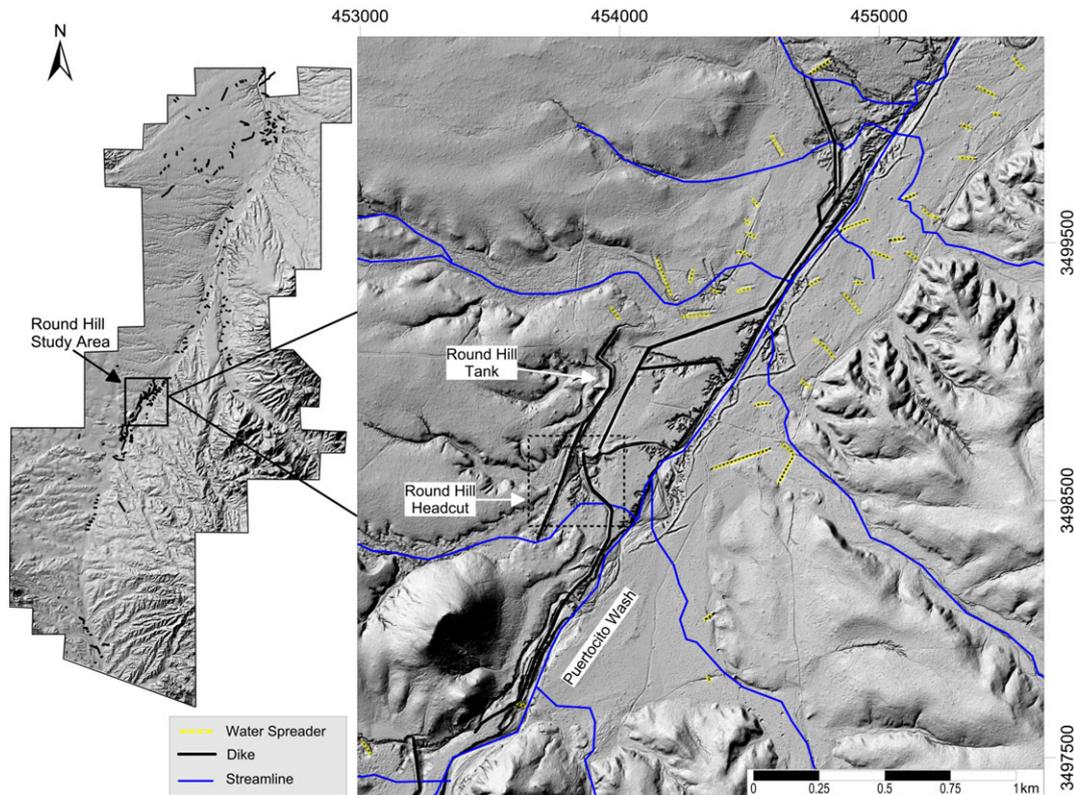
Interpreting the evolution of headcut advance is complicated by the apparent fact that over time repairs were made to breaches in the long berms. Although the drop-board gate was probably constructed in 1937, in the 1938 photographs the long berms are not visible and gullying is not evident. By 1956, a long berm and drop board gate are present, and the lateral runoff control berm is not breached. In 1974 the drop board gate is at ground level (no gullying), but the lateral berm



**Figure 2.** Oblique and aerial views of remnant water and erosion control structure types found on the US Fish and Wildlife Service Buenos Aires National Wildlife Refuge including (a) earthen stock ponds, (b) long earthen berms that control flood water runoff and lateral bank erosion, (c) concrete spillways, (d) shorter earthen water spreader berms generally found in floodplains, (e) drop board flow control gates, and (f) rock in wire gabion dams. Photographs (b) and (c) were taken after a prescribed burn, revealing berms that are normally obscured by grasses and shrubs. Although no longer functional, the gate in photograph (e) was operated by dropping boards between the iron uprights. Photograph (a) was taken by Brent Sigafus, US Geologic Survey, all other photos by the authors.

is breached approximately 30 m southeast of the gate. It appears that the breach was repaired, because in 2005 a different breach location can be identified approximately 100 m southeast of the gate, and a multi-lobed gully head is evident. Assuming the original breach was repaired in 1983 (half way between 1974 and 1992) the gully head is

advancing at a rate of  $4.8 \text{ m a}^{-1}$ . If the repair occurred earlier then the computed advance rate would be slightly greater, or approximately  $5.9 \text{ m a}^{-1}$ . Between 2011 and 2016, the area affected by gullying nearly doubled from approximately  $2600 \text{ m}^2$  to  $4550 \text{ m}^2$ , and about  $13\,000 \text{ m}^3$  of sediment was eroded.



**Figure 3.** The spatial distribution of long berms (dikes), water spreaders, and concrete water control structures with detail at Round Hill headcut site.

**Table I.** Summary of structure types, size, and condition based on 2015 aerial lidar data and visual assessment of 2016 aerial imagery

Structure (n)	Length (m) Mean (Min/Max)	Structural condition (n, (%))		
		breached	flanked	intact
Long earthen berm (27)*	755 (190/2437)	13 (48%)	4 (15%)	14 (52%)
Water spreader berm (218)	120 (14/981)	40 (18%)	37 (17%)	141 (65%)
Water control structures (29)**		5 (17%)	2 (7%)	22 (76%)
Stock tanks (117)		7 (6%)		110 (94%)
Rock gabions dam (3)***		1 (33%)	3 (100%)	0

\*two are breached and flanked

\*\*one of these structures is a drop spillway

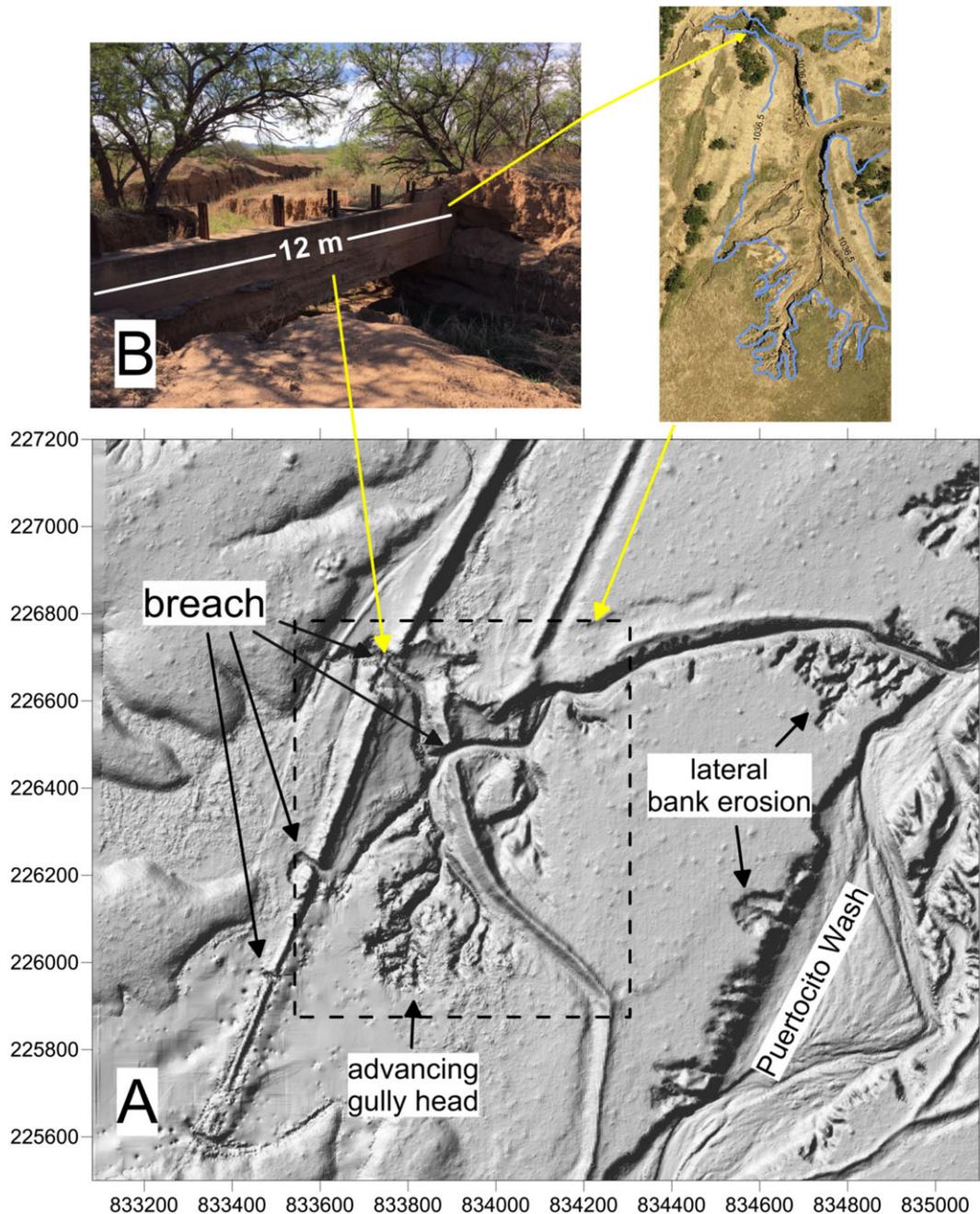
\*\*\*one is breached and flanked.

## Discussion

Abandoned water- and erosion-control structures that are no longer being maintained can induce localized erosion, gully-ing, and headcut advance. We have identified legacy structures as an important control on knick-point and gully-head generation, as well as scour and altered surface runoff pathways. Within the BANWR, earthen structures such as water spreader berms and long berms on floodplain and valley floor surfaces had the highest failure rate among common structure types. Breaching was the most frequent mode of failure, due to both concentration of surface runoff at weak points along berm crests and undercutting by advancement of downstream gully headcuts. It is important to note that although based on aerial imagery the incidence of structural failure among the stock ponds is low; they may not be operating as designed. Detailed field surveys are needed to assess storage capacity loss due to sedimentation and upstream hydrologic disconnectivities that limit potential inflow. All the observed rock-gabion dams, recently constructed to halt degradation within actively incising

channels, experienced lateral scour that contributed to structure failure.

Contemporary landscape evolution processes on the BANWR are complex, in part because the landscape is not only influenced by the relatively recent anthropogenic structures, but is also influenced by prior land-forming processes. To address the question of the importance of legacy impacts of water- and sediment-control structures for predicting how the landscape will evolve and determining what the legacy impacts mean for future land management, it is helpful to consider the time scales over which current controls on landscape forms and processes are operating. The framework presented by Hickin (1983) considered landscape change in geologic (millions of years), geomorphic (hundreds to a few hundred thousands of years), and engineering, or in our case land management (years to decades) timeframes. From a habitat restoration point of view (e.g. on the BANWR), time spans of years to a hundred years are particularly compelling because they represent the temporal scale of resource management affecting both ecologic and land forming processes (Peters *et al.*, 2006).



**Figure 4.** (A) Lidar image of Round Hill study area, (B) compromised drop-board water control gate, and (C) the extent of headcut advance as of 2015.

Geologic controls on landscapes determine the relief and topography that affect erosion and deposition (Brierley, 2010). This long time scale perspective provides a broad view of landscape patterns and dynamics that is beyond the temporal scale at which management decisions are made, and landscape change at this scale can be assumed to be constant (Hickin, 1983). The Altar Valley formed by faulting between 12 and 5 million YBP as the continent stretched and broke into blocks. Blocks that subsided formed valleys between higher adjacent blocks that eroded to form mountain ranges. Over time, the valleys filled with silt, sands, and gravels eroded from the ranges that connect to the valley floor across gently sloping bajadas (Bezy *et al.*, 2007). Floodplains formed as runoff generated in steeper, higher elevation reaches of the watershed slowed, spread, and deposited fine grained, cohesive sediment as it reached lower lying grass covered swales. Down-cutting events, which have increased in frequency over the past 4000 years (Bezy *et al.*, 2007) have eroded both the bajadas

and floodplains. The most recent down-cutting event that was initiated over a century ago has left the Altar Wash and many of its tributaries deeply incised. Currently, the Altar Wash is 4.5–6 m deep and average channel width has increased from 66 m in 1936 to 125 m in 1987 (Sayre, 2002). The entrenched drainage network is a direct geomorphic control on contemporary patterns of landscape change, and is expected to evolve toward a new equilibrium through lateral erosion and filling following the pattern conceptualized by Schumm (1977) termed the 'arroyo cycle'. This cycle has more recently been refined for southern Arizona (Webb and Hereford, 2010) and has been expanded to include headward migration of channels and inner floodplain formation as components of the arroyo evolution cycle (Gellis and Elliott, 2001). In fact, lateral channel widening and gullying can be observed along the main drainage and tributaries in Altar Valley, and in some places deposition is forming inner floodplains; however, at any given location the response is complex (Schumm, 1973; Schumm and Parker,

1973), affected by position in the valley floor, proximity to the main channel, and the presence of water and erosion control structures.

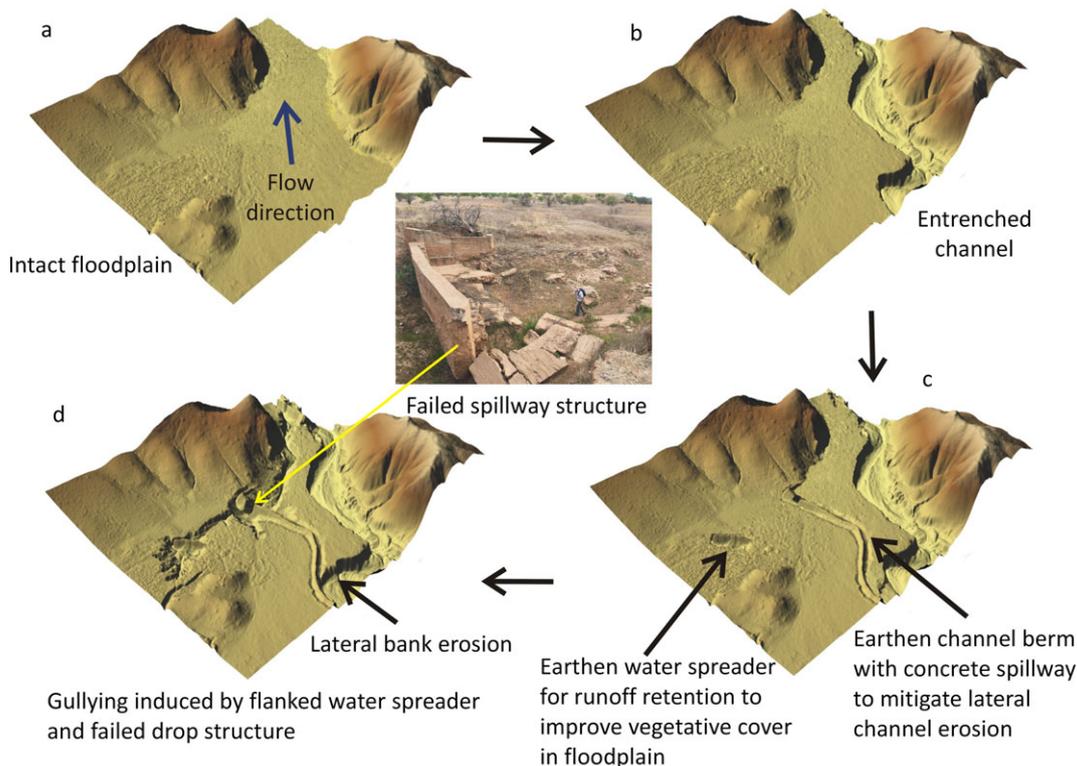
Many of the current water- and sediment-control structures on the BANWR and in the broader valley were constructed to mitigate lateral channel erosion by diverting runoff away from advancing gully heads and substantially limiting concentrated flow that drives headcut retreat (DeLong *et al.*, 2014). Gullies are unstable landforms (Knighton, 1998), and ultimately gully-ing and erosion in the headwaters of the Altar Valley will continue in response to regional channel entrenchment with the potential to last for centuries to millennia. However, in many cases current localized headcut initiation and incision on the BANWR is exacerbated by scour associated with unmaintained runoff and erosion control structures that has led to erosion and headcutting concentrated in areas of structural compromise. In the absence of mitigation, many of these erosion 'hot spots' will eventually connect to gullies that are responding to regional channel entrenchment presenting a risk to large expanses of grassland habitat.

A conceptual diagram of valley floor evolution as affected by both arroyo formation and water and sediment control structures is shown in Figure 5, which is generalized from conditions on the BANWR. Unincised valley floor conditions, reflecting balanced sediment supply and transport capacity, may persist for more than  $10^3$ – $10^4$  years (Figure 5(a)). Episodes of channel entrenchment, described as a component of the 'arroyo cycle' (Schumm, 1977), can be initiated by base level lowering, extreme floods, or the influence of human activity (Aby, 2017), reflecting erosive conditions that can occur rapidly and evolve over roughly centuries (Figure 5(b)). Within the time scale of land management planning ( $10^1$ – $10^2$  years), channel widening may be mitigated by constructing lateral channel berms to limit the extent of bank erosion (Figure 5(c)). In the western US, land management practices such as water spreading and the construction of berms are commonly

implemented to provide additional structural control over water distribution. In the absence of maintenance, structures designed to enhance water supply or mitigate erosion problems can themselves become the cause of localized headcut initiation, scour, and gullying (Figure 5(d)). Erosion associated with abandoned structures has developed over roughly the past three decades at the BANWR, but the expected duration of these geomorphic impacts is currently unknown.

Headcutting on the BANWR is expected to advance through the process of water driven mass wasting associated with saturation and direct wash over the headcut face (DeLong *et al.*, 2014; Rengers and Tucker, 2015). However, the response to any given runoff event can be highly variable, and the largest runoff events may not be responsible for the largest headcut and gully response (Nichols *et al.*, 2016; DeLong *et al.*, 2014). The headcut at the Round Hill site is advancing between 5 and 6 m  $a^{-1}$ . These average annual rates are higher than rates between 0.35 and 1.5 m  $a^{-1}$  recently reported for headcuts in southern Arizona (Rieke-Zapp and Nichols, 2011). However, the Round Hill rates may be higher simply because the rates are an average over 32 years in contrast to the 72 year time period covered by the Rieke-Zapp and Nichols study. Relatively low rates of gully head advance in Spain (0.07–0.51 m  $a^{-1}$ ) and Morocco (0–0.31 m  $a^{-1}$ ) contrast with rates reported from the west-African Sahel (3.16–9.85 m  $a^{-1}$ ) (Marzolff and Ries, 2007) and our current study. These previously reported average annual advance rates are useful for general comparison, but site specific conditions and highly variable rainfall and runoff can result in the advance rate of any given headcut being an order of magnitude larger than the average (Martinez-Casanovas, 2003). For example, large rainfall events and associated flooding from winter storms or decaying tropical storms (Webb and Betancourt, 1992) could cause rapid episodic headcut advancement thus compounding land-use management issues at the BANWR.

Critical to the goal of grassland restoration is knowledge of the extent of landform modification and the legacy impact of



**Figure 5.** Conceptual model of landscape evolution influenced by channel entrenchment and structures built to control surface water runoff and associated bank erosion.

these modifications on current hydrologic and landscape connectivity with important implications for ecological restoration. Floodplain earthworks have been shown to alter hydrology and affect floodplain ecology (Steinfeld and Kingsford, 2013), pointing to the need for explicitly considering structurally-induced gully erosion and altered runoff patterns when making management decisions. Alluvial floodplains are the most productive grasslands within the BANWR and many are covered with dense stands of Johnson (*Sorghum halepense*) and Sacaton (*Sporobolus wrightii*) grasses. These areas were the core habitat of the endangered Masked Bobwhite (*Colinus virginianus ridgwayi*), a subspecies of quail whose restoration was the principal rationale for the creation of the BANWR (Sayre, 2002). Even today, vegetative cover on many of the floodplains is dense enough that large areas are represented as data shadows in aerial lidar data, indicating no ground returns were detected. These grasses evolved with inundating sheet-flood flows, and headcuts currently working their way upslope are both physically reducing acreage and providing for drainage of prime floodplain habitat. Critically, gully erosion can, in many instances, be directly attributed to a specific structure. This presents an opportunity to prioritize and focus limited resources on sites where mitigation will be most successful because continued headcut advance and floodplain loss will constrain future management options.

## Conclusion

We investigated the legacy impacts of water- and erosion-control structures remnant of prior ranching operations in a semiarid landscape of southern Arizona, USA, where regional entrenchment is a dominant control on channel and floodplain evolution. Revisiting our initial questions, we conclude that gully erosion induced by unmaintained structures is a threat to large areas of productive rangeland. The geomorphic impact of legacy water- and erosion-control structures currently is evident as (1) localized gully erosion knick points induced by structure breaches and flanking, and (2) localized scour associated with concrete water-control structures that dictates runoff flowpaths and associated gully erosion. We developed a conceptual model that describes the relationships among evolution of the entrenched channel system, structures built to control associated bank erosion and surface-water runoff, and abandonment of the control structures following a land-use change.

Understanding the relationship between broader geomorphic instability and the legacy impacts of prior land use and manipulation is necessary for predicting how the landscape will evolve, as well as for developing achievable management strategies. Our study points to the importance of inherited land-use legacies on current and future management, even in landscapes where human alteration is not obvious. In the Altar Valley, watershed hydrologic and geomorphic process cannot be understood without taking into account the impact of legacy structures. The dominance of human interventions to control surface-water runoff and erosion is such that simply removing cattle from the landscape is insufficient to accomplish current management goals of grassland restoration. Since lateral bank erosion and gully head extension are ongoing processes of geomorphic adjustment within this semiarid landscape, preventing and mitigating erosion associated with abandoned structures is critical to limiting the extent and spatial distribution of rangeland degradation. In some cases, onset of disturbance is recent enough that opportunities for mitigation can be identified and potentially damaging erosion trajectories can be altered. Changing land use is an ongoing global phenomenon, and these changes often involve a loss

of local knowledge and historical management practices. Failure to incorporate land-use histories and legacies can lead to fundamentally mistaken prescriptions for land management and watershed health.

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