# 11 Ancient Infrastructure Offers Sustainable Agricultural Solutions to Dryland Farming

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## 11.1 INTRODUCTION

In arid and semiarid landscapes, water is the primary limiting resource for human activity and ecosystem functioning. More than 40% of the world's population lives in dryland environments

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(White and Nackoney, 2003). In these landscapes, annual rainfall can vary greatly and be highly unpredictable in both space and time. Longer intervals between precipitation events are also highly erratic and global atmosphere–ocean teleconnections, such as unusually cool Pacific Sea surface temperatures during the La Niña phase of the El Niño-Southern Oscillation, can trigger multi-decadal "megadroughts" (McCabe et al., 2004; Cook et al., 2016; Routson et al., 2016; Steiger et al., 2019). Soil moisture and local ecohydrology constrain the extent and intensity of food production possible through agriculture. Complex combinations of social and physical infrastructure have sustained population growth and managed hydroclimate risks in the past. Indigenous soil and water conservation has been tested over millennia to support agriculture (Johnson et al. 2021).

The focus of this chapter is the North American Southwest (NAS; Figure 11.1) and the resiliency of ancient and historic societies and cultural areas within. We draw broadly from the extensive literature and data collections of the US portion of this region to present a research overview and focus the scope of discussion on the unrecognized potential of Northwest Mexico. Simple rock and perishable material controlled surface water runoff for agriculture for thousands of years (DiPeso, 1974, 1984; Herold, 1965; Howard and Griffiths, 1966; Woodbury, 1961). These and higher-investment infrastructure, such as canals, terraces, and dams, are traditional solutions to concentrate soil and moisture to enable modes of subsistence production where it would otherwise be impossible (Kendal et al., 2011; Wilkinson et al., 2015; Norman 2020; Norman et al., 2022). Infrastructure modifications may permanently alter local hydrology, geomorphology, and productive capacity of the land, impacting both the size of the human population that it can support and the scale of the socioeconomic institutions required to manage it. In this way, the landscape becomes a palimpsest of successive modifications in which prior activity constrains and directs future development (Crumley and Marquardt, 1990). We use examples from the NAS to investigate and question the relationships between hydroclimate, infrastructure, and the socio-environmental trade-offs.

Physical and social infrastructure can support or sustain populations and manage environmental risk in the face of hydroclimate variability. Sometimes, sociopolitical systems may demographically overshoot long-term local carrying capacities during favorable climate periods while ossifying political and economic response potential (Anderies, 2006; Bocinsky et al., 2016; Ingram and Shelby, 2021). This can shift societal vulnerability from one set of shocks to another, trading off a reduction in shock frequency for an eventual increase in shock magnitude (Nelson et al., 2010). As changing climates reduce the amount of rainfall (megadroughts) yet increase potential for extreme events (megastorms), we are challenged to improve climate resilience to sustain growing populations (Norman et al., 2012; Norman, 2022).

Cumulative modifications to the physical landscape via infrastructure may alter hydrological cycles so greatly as to commit successive generations to predetermined strategies despite external drivers (e.g., climate change). Indigenous techniques have enhanced the sustainability and resilience of delicate dryland agroecosystems in the NAS through observation, cultural stewardship of the land, and innovation (Buckley and Nabhan, 2016; Johnson et al., 2021; Norman, 2020). There remain outstanding questions related to understanding how ancient agriculture might improve modern adaptability and resilience:

i. How exactly does infrastructure modulate the bidirectional feedbacks between hydrological variability, socioeconomic development, and the physical landscape on annual to decadal timescales?
ii. Can these feedbacks lead to persistent changes in regional hydrological cycles that constrain the centennial-scale evolution of these socio-hydrological systems to the present day?

While the spatial and social scales of infrastructural networks may have varied dramatically over time in the NAS, the underlying hydrological constraints and potential for socio-hydrological feedbacks have remained similar (Metcalfe et al., 2000; Pailes, 2017). Anthropologists of diverse theoretical

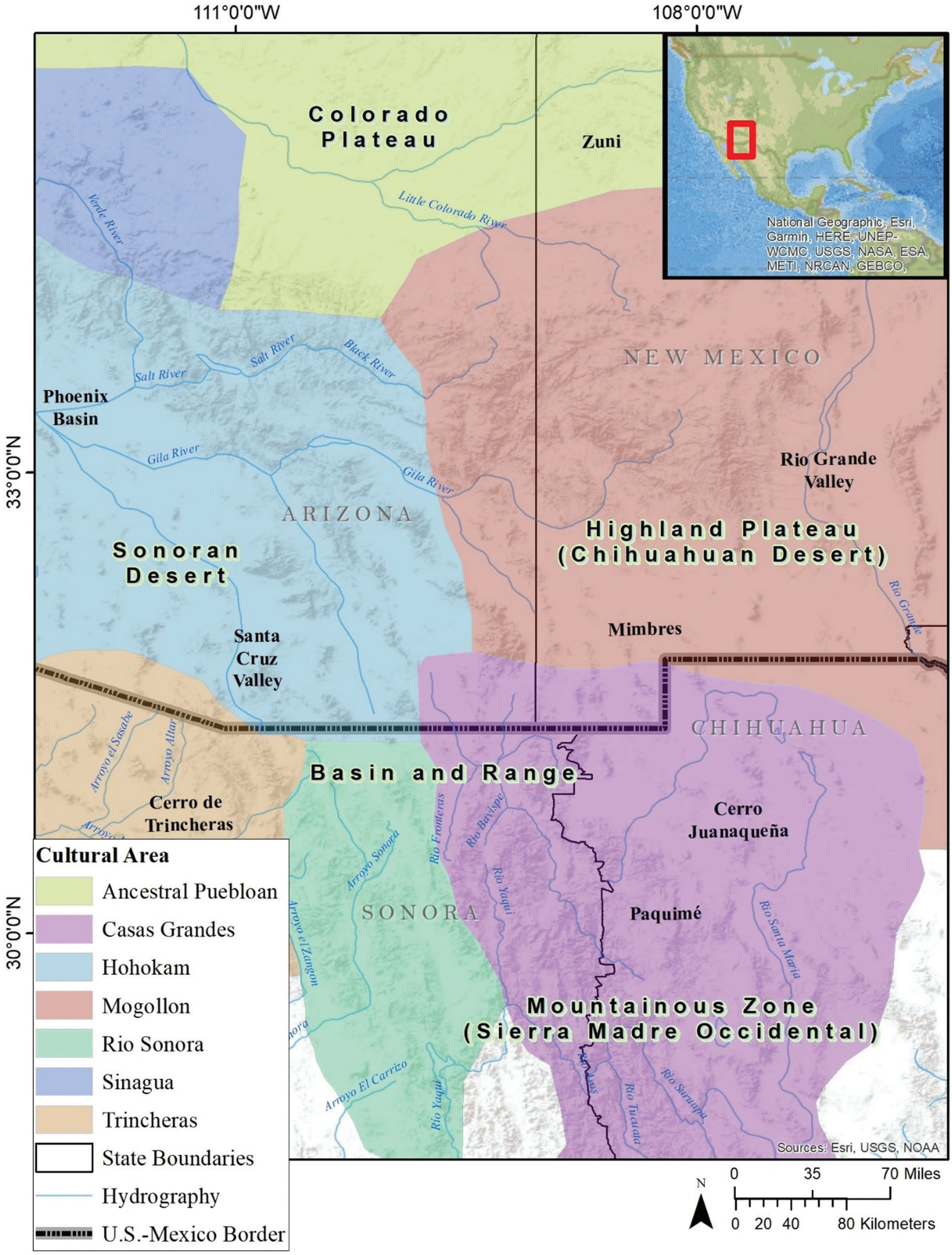

**FIGURE 11.1** Location map portraying the North American Southwest (NAS) study area, cultural areas (modified from Pailes 2017), hydrology, and geographical physiographic regions.

perspectives have further demonstrated that the economic configurations directly impacted by infrastructure, in turn, constrain and direct other domains of society, including politics and ideology (Engels 2010 [1884]; Kroeber 1939; Service 1962; Steward 1955). Understanding the long-term role of infrastructure in the NAS could inform present-day agriculture practices and provide a theoretical and empirical framework to help guide long-term water management efforts.

## 11.2 ANCIENT AGRICULTURE INFRASTRUCTURE

Subsistence agricultural production typified most of the NAS for the last 4,000 years, and much of the world for the last 10,000 years (Richerson et al., 2001). There is a wide range of variation in the organization of labor that was dependent on the specific intersection of ecology and technologies of production (Ingram and Hunt, 2015; Mabry, 1996; Matson, 1991; Tainter and Tainter, 1996). Over time, production regimes increasingly entailed a reliance on both physically modified landscapes and accumulated wealth of traditional ecological or indigenous knowledge (TEK/IK) tied to its effective management. We discuss varying types of infrastructure and associated traditional arid land water management for agriculture in the NAS including (i) foragers, (ii) direct-rainfall farming, (iii) surface runoff control, (iv) floodwater recession/small-scale irrigation, (v) irrigation production, and (vi) rangeland pastoralism (Figure 11.2).

### 11.2.1 Foragers

This mode of subsistence production relies on the collection and gathering of wild resources (Figure 11.2A). There is a continuum from immediate-return foragers who neither invest substantial effort into technologies to boost yields nor prolong their storage and delayed-return foragers who do make such investments (Woodburn, 1980). There is also a range of mobility patterns that typify foragers (Binford, 2001; Kelly, 2013). There is growing awareness that foragers modified landscapes, particularly using fire to manipulate vegetation cover and overall ecosystem diversity (Lightfoot et al., 2013; Roos et al., 2022). It is likely the most resilient of all economic systems but requires extensive land to support small numbers of individuals (Kelly, 2013). Periods of environmental stress, such as drought, are usually dealt with by activating social connections with neighboring groups and temporally leaving the impoverished area.

### 11.2.2 Direct-Rainfall Farming

This approach to horticultural production entails the lowest labor investment but is often the riskiest (Doolittle and Mabry, 2016). For our purposes, this term is defined as a plant-and-forget approach in which no substantial infrastructural improvements are made to increase yields or improve the odds of desirable outcomes (Figure 11.2B). In areas where there is reliable near-surface water, often due to an impermeable substrate or a very predictable precipitation regime, reliable harvests are attainable. In most cases, though, direct-rainfall farming in arid and semiarid environments carries a significant risk of failure and is most often practiced only in concert with less risky subsistence strategies as either a component of a diversified horticulture regime or an addendum to a largely forager existence (e.g., Griffin et al., 1971). As this method does not rely on permanent infrastructure, it does not typically produce cumulative investments. One exception to this rule would be the persistence of remnant stands of self-propagating cultivated resources that remain available to future populations (Nabhan et al., 2019).

### 11.2.3 Surface Runoff Control

This approach encompasses a wide range of methods and strategies to make use of rainfall and direct it to or within fields (Figure 11.2C). Common methods include modifying landscapes to

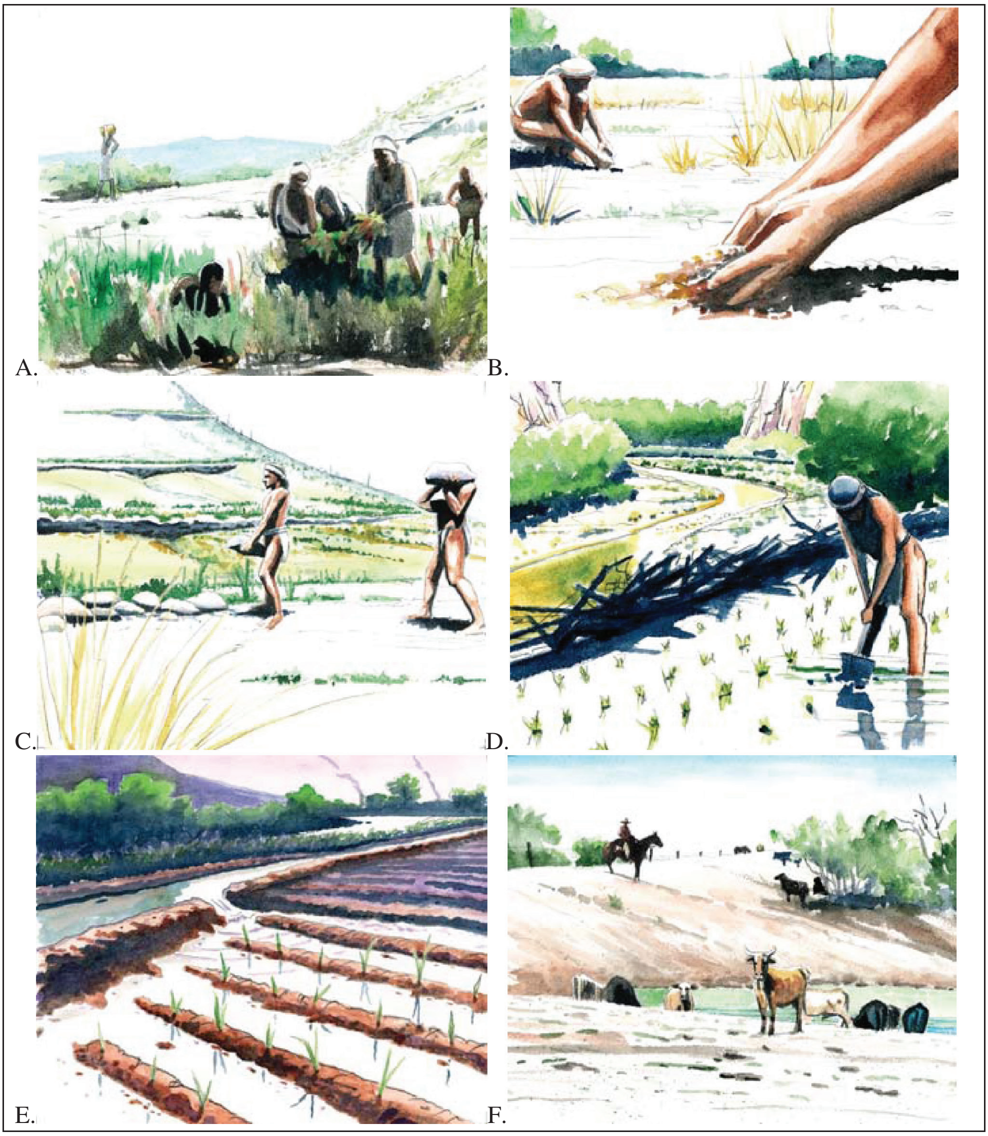

**FIGURE 11.2** Graphic depiction of documented ancient and historic water management and infrastructure for agriculture, with (A) foragers, (B) direct-rainfall farming, (C) surface runoff control, (D) floodwater recession/small-scale irrigation, (E) irrigation production, and (F) rangeland pastoralism. Illustrations by Caldwell Design.

accommodate crops through terracing of uplands with linear alignments, directing flows with water-spreading devices within expansive arroyo stream beds (e.g., *ak-chin*), constructing limited terraces (check dams) in drainages, and constructing rock mulches to retain direct precipitation (Doolittle and Mabry, 2016; Fish et al., 1992; Woosley, 1980). Researchers employ inconsistent terminology to describe similar runoff control features (Doolittle, 2000:64). The lexicon employed here attempts to use the most common terminology. These low-investment infrastructures are easy to install, coordinate, and operate, but require maintenance and periodic reestablishment. The discussion we present distinguishes these features and their associated strategies based on typical slope gradients and installment in or outside of channels (Figure 11.3).

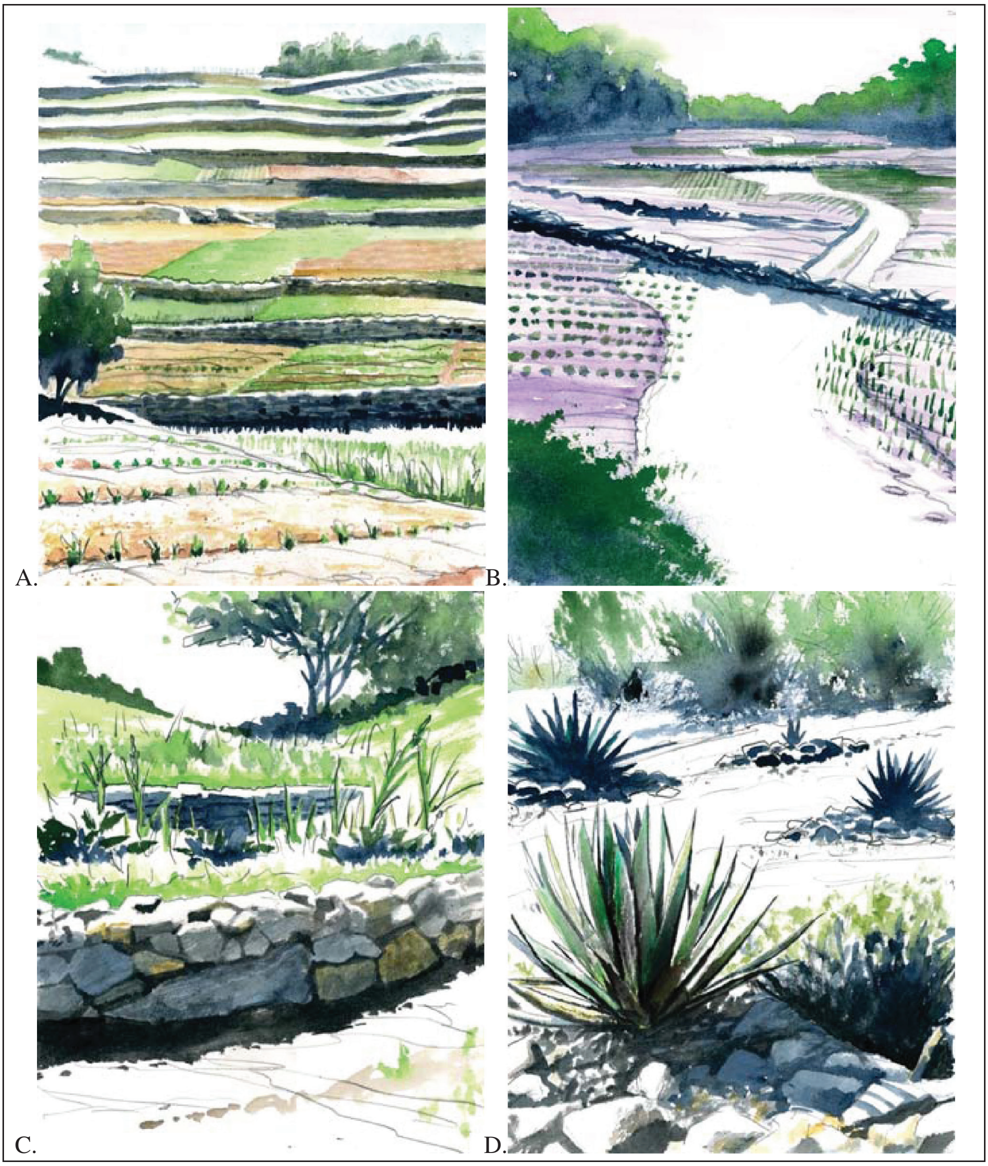

**FIGURE 11.3** Sketches of the four types of surface runoff control we describe in this chapter including (A) linear alignments, (B) water spreaders, (C) channel terraces, and (D) rock mulches. Illustrations by Caldwell Design.

### 11.2.3.1 Linear Alignments (Terrace Farming)

Linear alignments are constructed on gentle gradient hillslopes to create low terraces with cultivation plots (Figure 11.3A). Linear alignments are themselves a diverse class of features variably intended for soil and water conservation, by slowing peak runoff and thereby allowing more time for infiltration. They can aid in soil retention by slowing runoff and associated sediment transport, and in some contexts reducing the impact of wind on mostly level surfaces (Brown, 2012). There is a vast range of investments, ranging from labor-intensive constructions in which substantial soil and rock is purposively placed to simple rock alignments that slowly accumulate deposition over time. Vulnerabilities include the constant threat of droughts, soil exhaustion, and in many regions, years with insufficient growing seasons.

#### 11.2.3.2 Water Spreaders

Stream channels in dryland regions are often called *arroyos*, particularly when they are ephemeral or intermittent and incised into valley alluvium (Norman et al., 2022). Arroyo streams were some of the earliest contexts for farming in the NAS and remained productive focal points throughout most local sequences. Modifications are variable, but often take the form of spreading devices, such as brush anchored by rocks (Schaafsma and Brigs, 2007), intended to slow water speeds and direct them across small floodplains to various cultivation plots (Figure 11.3B). One specific example is *ak-chin* farming (Nabhan, 1986), which involves planting crops in seasonally dry arroyo beds and channeling over bank deposits onto fields in the rainy season. The scale of these systems is constrained by the available channel bottoms on which water can be effectively dispersed. Systems reliant on locationally heterogeneous isolated summer rains suffer dual threats of insufficient and overabundant precipitation that is often mitigated via modification of several distinct watersheds. Systems reliant on winter rains may be subject to more predictable and steady precipitation regimes but are limited by the effects of cold air drainage that shorten growing seasons in many regions. Channel bottom investments tend to be of less investment relative to main channel methods (Doolittle, 1988:49) and reflect a form of extensification as opposed to intensification. Investments in fields tend to occur on an annual or seasonal basis with limited potential for accretional annual growth.

#### 11.2.3.3 Channel Terraces (Check Dams)

This class of features is similar to the linear alignments and terrace farming but not established on hillslopes. These rock structures are built across small stream channels and vary in size depending on location in the channel (Figure 11.3C). Check dams are most often constructed in higher and steeper elevational settings. In upstream reaches, where gradients are steep, the structures are tall (≤ 2m) and spaced closely together, and in lower reaches, structures are shorter, wider, and spaced further apart. Like the larger linear alignment terraces, their primary function is to capture soil and slow the flow of water to allow greater infiltration. Plantings were often done right at the edge of stone walls. In some contexts, the primary purpose of check dams may have been to manage larger watersheds by preventing upstream gullying and sedimentation or siltation in depositional basins (Doolittle, 1985; Sandor et al., 1986). Channel terrace systems are susceptible to seasonal failures, depending on design, location, and precipitation intensity; seasonal maintenance and stewardship can reduce these vulnerabilities (Norman et al., 2022).

#### 11.2.3.4 Rock Mulches

A final method focuses on crops grown in rock mulches designed for direct-rainfall capture in otherwise unproductive zones (Figure 11.3D; Fish et al., 1992; Minnis et al., 2006). The principal benefit of rock mulches is to increase infiltration and reduce evaporation. There may be secondary benefits of improving soil nutrients and preventing fossorial root pests. The method is high risk when employed to grow plants near the limits of their water needs but can also be highly predictable when employed with xeric crops. In the latter case, long maturation periods expose the crop to other forms of risk (Pailes et al., 2018).

### 11.2.4 Floodwater Recession/Small-Scale Irrigation

These systems can vary greatly in size and complexity. Small- to medium-scale systems often intensively manipulate floodplains through investments such as living fencerows (Doolittle, 1988;

Nabhan and Sheridan, 1977) (Figure 11.2D). These investments can be expanded incrementally and serve to increasingly stabilize cultivation plots, capture fertile sediment, and slow flows to speeds amenable to small-scale irrigation networks. The narrowness of the river valley is typically the greatest constraint on infrastructural system's size and complexity. Droughts can regularly hinder the productivity of such systems, but floods can be catastrophic, removing accumulated soils and radically altering floodplain morphology. Some evidence shows that living fencerows make local gains at the expense of passing on the ramifications of floods to downstream neighbors (Doolittle, 2003). Measurement of the potential benefits and costs at various spatial scales and under variable flood periodicities and intensities would resolve this contradiction. Extant alternative interpretations indicate these systems may trade short-term gains and protection against mild floods for greater vulnerability to large-scale floods (Norman et al., 2010).

Larger scale flood water recession systems rely on the predictable timing of annual floods overbanking channels and soaking extensive flood plains. Though the annual timing of such floods is predictable there is still often great variation in their extent. Droughts can be problematic on a short-term basis, leading to crop failures if seasonal floods are insufficient to soak all planted areas. Floods can be catastrophic by destroying associated irrigation works and occasionally drastically altering natural stream channels. Moderate amounts of labor and long-term investments to regrow fence rows would be necessary to reclaim land after floods (Nabhan and Sheridan, 1977).

### 11.2.5 IRRIGATION PRODUCTION

Among the types of water management infrastructure employed in the world's drylands, irrigation technology represents the greatest degree of intensification through increased labor inputs (Figure 11.2E; Barlow, 2002). In a relative sense, very high yields can be produced from small parcels of land. Provided that there is enough water to meet system demands, irrigation also allows the greatest control over production. Droughts are problematic for irrigation systems in the short term and often lead to internal strife among communities of users over water allotment (Sheridan, 1996). Floods can be disastrous and render an entire system inoperable, necessitating massive amounts of coordinated labor for repair efforts (Woodson, 2015). The most disastrous of floods can entrench river channels making previous canal heads unusable and requiring a near-complete redesign of the system (Waters and Ravesloot, 2001). Irrigation systems are by their nature hierarchical in structure, and the nested branching of an irrigation system may reflect social units responsible for system upkeep (Hunt et al., 2005).

### 11.2.6 RANGELAND PASTORALISM

Pastoral production relies upon domesticated animals (Figure 11.2F). Arid land pastoralism needs extensive land holdings and access to water and may result in conflicts with other production strategies. The introduction of pastoral agriculture typically increases regional carrying capacities by integrating large swaths of relatively unproductive land into new production systems (Sheridan, 1992). Stock ponds or water impoundments are critical for rangeland animals and are created by damming small watersheds and often supported by groundwater pumping in modern economic systems. In addition to environmental risks of drought that reduce water and forage to below acceptable thresholds, pastoralism is susceptible to social perturbations that restrict land access or lead to theft of resources (Radding, 1997; Sheridan, 1995). Strong social contracts that facilitate communal use of grazing lands are a common corollary of pastoral economies (Cohen, 1974). Pastoral systems allow for the inter-annual accumulation of subsistence resources in a categorically different form than crops and were therefore associated with greater levels of political complexity and inequality (Kohler et al., 2017).

## 11.3 CULTURAL ANTHROPOLOGY, GEOGRAPHY, AND HYDROCLIMATE GEOMORPHOLOGY (WHO, WHAT, WHERE, WHEN, AND WHY)

Previous studies have extensively documented anthropogenic landscape modifications in the US portion of the NAS, demonstrating that ancient subsistence infrastructure significantly altered ecohydrology and soil systems, and in many instances continues to do so today. Notable examples include substantial rock mulch fields in the Rio Grande region (Lightfoot and Eddy, 1995); extensive rock pile fields dispersed across southern Arizona (Fish and Fish, 2004); Hohokam irrigation networks, which provided the template for modern systems in the Phoenix Basin (Turney, 1922); and extensive and diverse systems of surface runoff control across the Colorado Plateau (Bryan, 1929; Woodbury, 1961). The continuing impacts of these features are readily visible in the formation of anthropogenic soils (Minnis and Sandor, 2010; Sandor and Homburg, 2017), moisture retention and resultant flora distributions (Doolittle and Neely, 2004), accumulations of fine-grained sediment or salinization in the case of canals (Huckleberry, 1992; Nials et al., 1989), and modifications of drainage patterns (e.g., Wilhusen et al., 1997).

In the remainder of this section, we discuss the Mexican portion of the NAS to illustrate the magnitudes of landscape modification. To facilitate discussion, we divide the Mexican NAS landscape into four distinct topographical ecozones and discuss their different sociopolitical systems. These systems were in turn reliant on variable combinations of agricultural infrastructure embedded in the larger subsistence economy. These zones largely correspond to the current iterations (Pailes, 2017) of culture areas long utilized in anthropology (Wissler, 1927) as a starting point for demarcating differences in social group affiliations. Each incorporates much of the same total elevational and precipitation range, lending to their bioclimate and vegetation distinctions. Ancient and historic inhabitants accordingly employed the full suite of agricultural water management infrastructure suitable to particular humidity and topographical contexts across all of these ecozones. The regions differ markedly, though, in the relative reliance of groups on different niches. This ecological variation in concert with historically contingent demographic processes led to substantially different relative frequencies of alternative water management strategies in the four ecozones. Table 11.1 illustrates these alternative approaches to water management that were tested at different timescales, with only one or two methods typically becoming dominant approaches to production in a given ecozone over long timeframes.

The four ecozones are as follows: (1) a moderately high-altitude plateau (~1,100 m) dominated by semiarid grasslands with perennial rivers; (2) a rugged, mountainous zone with diverse topographically mediated ecozones (maximum altitude ~3,300 m), ranging from thorn scrub to pine woodland; (3) a basin and range province dominated by narrow river valleys (~700 m) with perennial rivers characterized by thorn scrub and deciduous forest; and (4) the open basins of the lower Sonoran Desert (Peinado et al., 2010). Though the terrains, ecosystems, and climates of these regions are diverse, the subsistence production of the first three was ultimately reliant on precipitation that fell in the mountainous zone or rainfall patterns that exhibit synchronicity with this region. The following section describes the configurations of environment, infrastructure, and sociopolitical organization that characterized each ecozone (Table 11.1; Figures 11.1, 11.2, and 11.3). We attempt to note the corresponding descendant communities for the ancient traditions discussed in each ecozone. However, data are often limited and noted affiliations are not intended to be exhaustive or exclusive.

### 11.3.1 MEXICAN HIGH PLATEAU (CASAS GRANDES CULTURE AREA)

Agricultural communities have an ancient time depth in this region, beginning with the occupation of the large, terraced hill site of Cerro Juanaqueña (Figure 11.1) by 1200 BCE. The terraces at this

### TABLE 11.1

### Table Crosswalks the Relationship Between Ancient Infrastructure for Water Management and Food Production with Cultural Groups, Geographical Physiographic Regions of the NAS, and the Approximate Time of First Employment

| | | **Colorado Plateau and Adjacent Uplands** | **Highland Plateau (Chihuahuan Desert)** | **Mountainous Zone (High Sierra Madre)** | **Basin and Range (Valley Sierra Madre)** | **Sonoran Desert** |
|---|---|---|---|---|---|---|
| *Cultural groups* →↓ *Infrastructure* | | **Ancestral Puebloan, Sinagua** | **Casas Grandes, Mimbres and Jornada Mogollon** | **Casas Grandes, Serrana** | **Rio Sonora** | **Hohokam, Trincheras** |
| **2.1 Foraging** | | prior to 10,000 BCE | prior to 10,000 BCE | prior to 10,000 BCE | prior to 10,000 BCE | prior to 10,000 BCE |
| **2.3 Surface Runoff Control** | **2.3.1 Linear alignments** | 900 CE | 1200 BCE (Cerro Juanaqueña) | *1200 ce* | – | 800 CE (Phoenix Basin) |
| | **2.3.2 Water spreaders** | 1200 BCE (Cerro Juanaqueña) | – | *500 ce* | 1700 BCE (Santa Cruz valley) | – |
| | **2.3.3 Channel terraces** | 400 BCE | *1200 ce* | *1200 ce* | *1200 ce* | – |
| | **2.3.4 Rock mulches** | 850 CE (Zuni) | *1200 ce* | – | – | 800 CE (Phoenix Basin) |
| **2.4 Floodwater recession** | | 1100 CE (Sinagua area) | 650 CE (Mimbres) | – | *500 ce* | – |
| **2.5 Irrigation** | | 1000 BCE (Zuni) | *1200 ce* | – | *1000 ce* | 1500 BCE (Santa Cruz valley) |
| **2.6 Pastoralism** | | – | 1700 CE | 1700 CE | 1600 CE | 1600 CE |

*Sources:* Cordell and McBrinn (2012); Crown (1987); Hanselka (2018); Hard and Ronery (2020); Lightfoot (1996); Matson (1991).

*Note:* Dates in italics are minimally investigated regions and likely underestimate antiquity of first employment.

site were primarily domestic (as opposed to agricultural) and provided the living space for at least seasonally sedentary population that farmed the nearby Rio Casas Grandes floodplain presumably with techniques such as floodwater recession and perhaps small-scale irrigation. Smaller sedentary population sites on terraced hills of a similar age are present in neighboring valleys (Roney and Hard, 2004; Hard and Roney, 2020), and researchers have only begun to catalog the early history of land modification in this region.

Two millennia later (800 CE), the high plateau of Northwest Mexico was home to Paquimé, one of the largest and most politically complex precolonial polities in temperate North America (DiPeso, 1974; Kelley, 2017; Whalen and Minnis, 2009). This large population center dominated economic activity across a sizeable portion of the upland plateau region in the Casas Grandes valley and was clearly dependent on irrigation. Some research suggests these populations may be related to antecedent Mimbres groups of the US NAS who practiced small-scale irrigation by 650 CE (Nelson et al., 2010). At the apogee of Paquimé, ca. 1300 CE, irrigation production was likely substantial, as indicated by the relatively abundant modern stream flow and the substantial and amenable floodplain (Doolittle et al., 1993). Irrigation agriculture focused on common New World cultigens, particularly maize.

Surface runoff farming with linear alignments and rock mulches was another major focus in much of the Casas Grandes core region. This form of landscape modification reflects a means of extensification that brought upland areas under cultivation in several regions of the NAS (Fish and Fish, 2004:219). It is likely that annual crops, such as maize, were grown in particularly salubrious areas of the Casas Grandes region, but *Agave* (sp.) was the most widespread crop owing to its lower water requirements. Individual plots composed of thousands of meters of linear rock alignments tend to be less than 10 km$^2$ in area, but the ubiquity of sites is still not fully assessed (Minnis et al., 2006). The absolute scale of irrigation agriculture and surface runoff control fields remain unquantified south of the border.

The end of the Casas Grandes sequence remains an archaeological enigma. By ca. 1500 CE complex sedentary societies no longer inhabited the region, being replaced by or transitioning into foraging societies (Suma, Conchos, Jano, and Jumano) that were in turn forcibly excluded from subsequent colonial economies that focused on pastoralism and reconstituted irrigation networks.

### 11.3.2 MOUNTAINOUS ZONE (PERIPHERAL CASAS GRANDES)

The high-mountain communities in the western portion of the Casas Grandes cultural area are the least known at present (Figure 11.1). Sedentary populations were clearly present in these areas from at least 1000 CE (Bagwell, 2004; Martínez and Jaramillo, 2013). Rare foreign artifacts indicate connections to regional traditions known from both the high plateau and the basin and range province (Gamboa and Mancera-Valencia, 2008). It is presently unclear if these high-elevation populations reflect refugia that were used in times of ecological or social stress, opportunistic expansion associated with periods of salubrious ecological and social conditions, or persistent occupation largely independent from neighboring ecozones. Owing to the steep slopes of the region, the only viable subsistence production options were direct-rainfall farming and surface runoff control, with a particular emphasis on drainage terraces (check dams). In all cases, the extent of individual plots under cultivation would be limited, but the overall scale was potentially substantial (Herold, 1965). Charles Di Peso (1974, 1984) was so impressed by the ubiquity of such features that he speculated they altered the essential character of water and sediment flow into the Casas Grandes and neighboring valleys. Though this claim is unsubstantiated, it speaks to the possible scale of the landscape modification, which remains unquantified almost 50 years later. The transition to the historic era is less well documented in this region. Various nonagricultural lifestyles focused on foraging, mounted raiding economies (Ndee [Apache]) dominated much of the region (Radding, 1997). In some areas, semi-nomadic agriculturalist communities (Raramuri [Tarahumara]) persisted throughout the historic and modern eras and serve as a likely analogy for ancient lifeways as well (Graham, 1994).

### 11.3.3 Basin and Range Valleys (Rio Sonora)

The province of eastern Sonora pertains mostly to the Rio Sonora culture as well as portions of the Serrana. This region includes at least 35 distinct river valley segments as inferred from topographical boundaries and the distribution of modern populations (Figure 11.1; Doolittle, 1988; Pailes, 2016). Agricultural economies developed by around 500 CE (Douglas and Quijada, 2004) and became ubiquitous by 1000 CE. The precolonial (prior to mid-1500s CE) subsistence economy of the region relied on a mix of small-scale irrigation and floodwater recession in the limited floodplains of valley settings. Floodplains in this region are spatially limited, bounded by steep terraces (~10 m), and broken into numerous local reaches by narrow canyon sections. Presently available floodplains are highly modified and under near 100% cultivation in a completely anthropogenic hydrological regime with modern irrigation ditches operated alongside generations of traditional living fence rows (Nabhan and Sheridan, 1977). In ancient times, a range of surface runoff farming methods were employed in more spatially constrained arroyo settings, and rarely direct-rainfall fields were planted as high-risk additions (Doolittle, 1988). Similar agricultural methods remained in use well into the historic period alongside newly introduced pastoral economies. In contrast to most portion of the NAS, this region maintained large populations until the period of intensive colonial intrusion in the 1700s (Doolittle, 1984a, 1984b). The topographically and ecologically constrained scale of polities likely contributed to the persistence of populations in this region (Pailes, 2017). In the absence of large-scale regional political consolidation, local collapses could not propagate throughout the entire region. In the historic era, the indigenous Ópata, Eudeve, Jova, and Nebome [Lower Pima] of the region were incorporated into mestizo populations, with a few towns retaining distinct indigenous identities. Throughout the otherwise tumultuous colonial period, there was continuity in traditional farming practices that were slowly modified to increasingly emphasize pastoralism.

After flowing through the mountains, the perennial rivers of this region enter a broad and flat coastal plain. In this region, large-scale floodwater recession and irrigation are possible and were employed historically by Yaqui (Yoeme) and Mayo (Yoreme) groups. There is very little archaeological data on this region, known archaeologically as the Huatabampo, but it clearly ranks as one of the most productive in all of the NAS and today is one of the most thoroughly modified by agricultural activity.

### 11.3.4 Low Sonoran Desert (Trincheras)

The low Sonoran Desert of northwest Sonora, Mexico, was dominated by the Trincheras culture. The term *trincheras* requires a parenthetical discussion. Trincheras literally translates as “fortification” in most contexts but has become a catchall term for low stonewalls and is often applied to the agricultural features we describe as terraces or check dams. The Trincheras culture discussed here received this name from a common site type in which dry-laid masonry walls were constructed on low volcanic hills. The resulting terraces likely supported some amount of domestic garden plots (Fish et al., 1984) but were not primarily agricultural in nature (Downum, 2007). To add a last level of complication, these hill sites, known as *cerros de trincheras*, occur in many culture areas of the Southwest.

The Trincheras sequence emerges from local forager roots roughly contemporaneously with northern Sonoran Desert regions occupied by the Hohokam (Carpenter et al., 2018). At the La Playa site, located on a tributary of the Rio Magdalena, canals were employed by 1200–800

BCE (Cajigas, 2019; Copeland et al., 2012). Near the end of this period, significant downcutting precipitated a major demographic realignment. Much of the subsequent cultural sequence remains unclear or known from only limited investigations. In the Altar valley, Trincheras populations developed locally until an intrusion by more northern Hohokam groups forced an exodus around 1300 CE (McGuire and Villalpando, 1993). This region would be most conducive to various forms of surface runoff focused on seasonally dry stream beds. Coincident with the Altar depopulation, the Magdalena Valley's population grew, presumably reflecting an influx of migrants. This growth culminated in the construction of the site of Cerro de Trincheras, the largest exemplar of a terraced hill in the NAS with up to 1,000 inhabitants (Villalpando and McGuire, 2009). This site was relatively short-lived, with another major depopulation event occurring coincident with similar demographic declines in the Hohokam region at ca. 1450–1500 CE. The setting of the Magdalena Valley suggests farming strategies included irrigation from the near perineal river and surface runoff floodwater farming in channels. These inferences are based on analogy with the extensively studied Hohokam of the US NAS, which constructed the largest canal system in all of ancient North America in the Phoenix Basin (Figure 11.1). Descendant communities of both the Hohokam and Trincheras include diverse O'odham and possibly Yuman groups, who continued to practice many of the same productive strategies at smaller scales into the modern era supplemented by substantial pastoralism.

## 11.4 HISTORIC SOCIO-ENVIRONMENTAL BALANCING

Across variable topographical and ecological zones of the NAS and throughout time, there is variance in the productive infrastructure constructed, the crops or animals employed, and the associated distribution of reliant populations. As noted, most ancient infrastructure for water management and food production was utilized in each ecozone but was often deployed in a different order and, more importantly, usually with one or two methods becoming uniquely dominant. People who lived on the High Plateau and Sonoran Desert, with broad basins, mainly irrigated. Those occupying mountainous zones had to use upland strategies to control surface runoff, that is, check dams. And people who lived in the narrow Basin and Range valleys adopted small-scale irrigation and flood water recession. These strategies existed in a dynamic reciprocal relationship in which populations respond not only to external drivers, such as precipitation, but also to the cumulative effect of past infrastructural investments which altered the character of ecosystems and water budgets. These relationships have alternatively constrained or amplified the impact of various magnitude shocks that ultimately determined the resiliency of sociopolitical configurations. The several major demographic adjustments noted in the previous section highlight the most drastic of potential outcomes that invariably result from the complex interaction of environmental and historically contingent factors.

There are many mitigating strategies that can be followed to reduce risk to an overall subsistence economy. However, these strategies are often hard to enact without coordinated, group-level efforts, which are often resisted by autonomous production units – most often households (Netting, 1993; Wilk, 1989). At a very general level, arable land scarcity and attendant higher labor inputs per unit of production yield tend to be correlated with increased economic and social inequality (Mattison et al., 2016; Smith et al., 2010). The capacity for such systems to produce surplus commodities and labor frequently leads to the emergence of political configurations demanding tributes (Earle, 1997; Hayden and Villeneuve, 2010; Wolf, 1982). A key factor in explaining why increasing inequality is tolerated in these contexts is that the new political formulations may contribute to greater resilience through features such as effective hierarchical control (Johnson, 1982). However, the formation of integrative institutions also introduces new vulnerabilities, such as rigid response systems (Janssen et al., 2003; Janssen and Scheffer, 2004).

### 11.4.1 CASE STUDIES

Regarding the resilience of physical systems of horticulture and agriculture, greater investments in infrastructure are generally driven by positive feedbacks between labor and resource consumption demand (Bocuet-Appel and Bar-Yosef, 2008), which often increase the risk of catastrophic production failures should that infrastructure be destroyed. Previous research provides five case studies from the NAS that provide insights on what are likely common sustainability trade-offs and trajectories of ancient agriculture.

I. The Hohokam culture developed an increasingly complex and integrated system of sociopolitical and physical canal infrastructure for a millennium. However, when the sociopolitical systems that facilitated regional exchanges began to fray coincident with several flood and drought-induced shocks (Hill et al., 2015), the resulting turmoil soon prevented effective upkeep of the physical canal infrastructure, leading to a substantial regional depopulation (Nelson et al., 2010).

II. Floodplain farming in the Mimbres was complemented by place-based sedentism that ultimately exacerbated resource depletion. In response, smaller settlements were established with similar infrastructure, extending regional trajectories under new social formulations (Nelson et al., 2010).

III. The Zuni water infrastructure was relatively small scale and supported more flexible social groups. As a result, periodic perturbations had only muted impacts (Nelson et al., 2010). However, cautionary tales from other portions of the neighboring Colorado Plateau suggest that sociopolitical production goals often led to increasing populations that could ultimately not be sustained in the face of climatic downturns. The resulting human responses of violence and mass migration bespeak an outsized response that ultimately entailed the complete abandonment of large regions (Schwindt et al., 2016).

IV. During the height of the occupation of the Cerro de Trincheras there is evidence for a basin-wide integration of the community through shared hilltop rituals (Fish and Fish, 2004). There are few of the typical signs of emergent political or social inequality in this region (McGuire and Villalpando, 2011). The aforementioned downcutting early in the Trincheras sequence, the 1450 CE depopulation of the region, and possibly the shifting cultural boundaries of intervening periods in the Altar Valley may all reflect populations heavily impacted by environmental perturbations to fragile subsistence infrastructure.

V. Though details vary, most archaeologists envision Paquimé as an administrative center that received surplus production tribute from a substantial hinterland and in turn provided access to either rare goods or ideological and social legitimization (Di Peso, 1974; Rakita, 2015; VanPool et al., 2005; Whalen and Pitezel, 2015). The symbolic control of water and the infrastructure through which it flowed are manifest components of the ideological system of Paquimé (Walker and McGahee, 2006). Elite status at Paquimé and its underpinning political institutions relied heavily on the appearance of effective control over precipitation (Cunningham, 2017). Both the center and larger regional populations declined precipitously sometime around 1450 CE (Whalen and Minnis, 2012). Owing to a lack of environmental reconstruction in Northwest Mexico, it is unclear if this downturn was ultimately caused by a short-term environmental triggering event or by a gradual overextension of productive capacity. Political, economic, and regional demographic collapse were synchronous in this case.

### 11.4.2 TRADE-OFFS (ROBUSTNESS VS. VULNERABILITY)

Infrastructure for water management is a crucial cultural innovation and adaptation to the challenges of living in arid lands, but it is not a perfect solution. Physical structures decay with time, and water management systems require significant investments of time and energy to maintain and monitor (Purdue, 2015; Huckleberry et al., 2018; Norman et al., 2022). Problems demanding collective action inevitably arise between the users of public infrastructure and those responsible for provisioning it (Cifdaloz et al., 2010; Anderies et al., 2013; Muneepeerakul and Anderies, 2017). Ultimately, infrastructure increases a society's resilience to water scarcity and environmental risks by shifting its vulnerability from one set of shocks to another (Janssen et al., 2007). Three trade-offs can be identified in all of these five case studies and from the broader resilience literature:

i. *Magnitude (Shock)–Frequency*: Physical infrastructure increases robustness to high-frequency events like small- to medium-size floods and intermittent droughts, but at the cost of increased fragility to low-frequency events like extreme floods or megadroughts (Anderies, 2006; Huckleberry et al., 2018; Norman et al., 2010).
ii. *Place-Based Lifestyles–Local Resource Degradation*: Physical infrastructure increases social, cultural, and behavioral commitments to specific places on the landscape and specific strategies of production, leading to long-term resource depletion and reduced resilience (Janssen et al., 2003; Janssen and Scheffer, 2004; Anderies and Hegmon, 2011).
iii. *Slow–Fast Variable*: Physical infrastructure attenuates short-term variability in food production (a fast variable) yet allows for long-term population concentration and growth (a slow variable) which can eventually outstrip the carrying capacity (Ertsen et al., 2014; Tellman et al., 2018).

What unites these trade-offs is that the socio-hydrological vulnerabilities arise only on long, intergenerational, timescales. Despite natural resilience, seemingly stable ecosystems and social networks alike are susceptible to abrupt and drastic changes when they reach their tipping points. Because different infrastructure systems reduce variability, risk, and vulnerability in the short term, the more devastating shifts happen slowly, often beyond the ability of any individual person to fully perceive. Historically, flexibility of humans to organize (or reorganize) to dispersed transient settlements and to extend their social networks helped balance trade-offs and provided time for ecohydrological systems to recover (Nelson et al., 2010).

## 11.5 FUTURE RESEARCH

The utility of long-term demographic and socioeconomic data for addressing questions of present-day societal adaptation to climate has been limited, especially in multinational settings. There is a lack of understanding related to environmental impacts of ancient agricultural infrastructure that arises from limited long-term climatic and archaeological records resolved at similar spatial and temporal coverage. An integrated socio-hydrological modeling approach could help address this gap. It is not enough to simply inventory, map, and assess the condition of ancient and historic infrastructure systems as has been typically done by archaeologists. We hypothesize that the installation of infrastructure for water management has significantly altered the hydrological functioning of landscapes on centennial timescales. For example, research on surface runoff control features, such as those preserved across the NAS, indicates that they continue to increase subsurface infiltration, downstream flow volume, soil productivity, and vegetative response (Callegary et al., 2021; Norman et al., 2014, 2016, 2019, 2022; Wilson and Norman, 2018, 2022). Data on the age and distribution of ancient water management infrastructure could be combined with hydrological models to understand how these features Awkward may continue to alter surface water and subsequent sedimentation and geomorphology.

We hypothesize that in ancient and historic agricultural societies:

i. years of higher-than-average rainfall correspond to increased socioeconomic growth, particularly demographic growth, and those with lower-than-average rainfall correspond to slower or negative growth;

ii. periods of sustained demographic and socioeconomic declines have occurred after alternating extreme dry and wet years;
iii. water management infrastructure has led to sustained increases in local carrying capacity on decadal timescales; and
iv. this infrastructure continues to modify regional ecohydrology and sociopolitical systems on millennial scales.

Much of the data to evaluate these hypotheses are available in Northwest Mexico that could be incorporated with extant reconstructions of the US NAS to achieve an integrated regional approach. A substantial documentary record exists for the Spanish and Mexican water management infrastructure and landscape modifications of the historic period (1540s–1850s). And there is substantial published data on demography and institutional arrangements for this period, much of it based on Jesuit and Franciscan mission "*anuales*" (e.g., Griffen, 1979; Reff, 1991; Radding, 1997).

For the precolonial period, archaeologists have already generated baseline analyses of the institutional arrangements, land-use patterns, and political trajectories for much of Northwest Mexico. Elements that are currently lacking include refined approaches to reconstructing demography and climate. Existing and ideally expanded carbon ($^{14}C$) dating datasets could be employed to project demographic responses to socio-hydraulic systems into the ancient past. The frequency of $^{14}C$ dates can serve as a measure of demographic density on the assumption that anthropogenic deposits (the targets of numerical dating) accumulate in proportion to population size (Brown, 2015; Edinborough et al., 2017; Peros et al., 2010). Furthermore, centennial tree-ring chronologies have been developed for some portions of Northwest Mexico and others are in progress; in the US NAS, these proxy records are much longer and complete. Substantial curated tree-ring records are available for the past 1,000 years that await analyses. Lastly, there is potential for isotope analyses to be used to identify areas of high carbon sequestration in agricultural infrastructure (Callegary et al., 2021; Norman et al., 2022).

The back-casting of watershed-scale hydrological models could capture complex interactions between precipitation, the geophysical landscape, and local ecohydrology and simulate natural infrastructure in dryland streams, including the flow of water and associated transport of sediment (Norman and Niraula, 2016; Norman et al., 2017). Long-term estimates of where and how much water flows over a study area, and how ancient water management infrastructure influenced these flows when actively maintained or abandoned could be estimated to help further understand their impacts. Interdisciplinary cooperation across administrative boundaries and cultures may enhance the understanding of past climatic, demographic, and socioeconomic changes and elucidate long-term socio-hydrological dynamics and beneficiaries (Norman et al., 2013). Indigenous agricultural systems are rooted in long-term, place-based experience and deep ecological understanding, adapted through generations and generations of droughts and floods (Johnson et al., 2021; Norman, 2020). Given a clearer image of the diversity of cultural and environmental contexts of past infrastructure systems, models can be applied to assess varying robustness–vulnerability trade-offs inherent to each to circumvent losses in the future.

## 11.6 CONCLUSIONS

In this chapter we have reviewed emerging interpretations of the relationship between ecohydrology, water management infrastructure, and sociopolitical systems in the arid NAS. Over a century of research in the US NAS provides informative case studies for inferring basic relationships of resilience that center on the inherent trade-offs of short-term variance reduction at the expense of increased exposure to rare but extreme events. A key element in this discussion that is currently undocumented is how cumulative landscape modification, including water management infrastructure, constrains and alters both ecohydrology and sociopolitical systems. We call for a fuller integration of existing work and a much greater effort to include the vast understudied portions of Northwest Mexico in future research. This portion of the NAS provides several additional case studies from ecologically diverse arid lands settings to further asses the relationships of resilience hypothesized in extant literature. This effort will require a multi-pronged approach to synthesize existing historical and archaeological data with newly expanded climate proxy data and watershed models. We believe the potential benefits of this research program are far more than academic. The long-term physical memory of pre colonial and historic agricultural systems can be embraced and leveraged as possible nature-based solutions to modern management problems. This call is in line with the increasingly acknowledged potential of indigenous knowledge to anticipate long-term socio-hydrological dynamics that facilitate resilient agricultural production. Climate change, agricultural food security, and human migration are components of this complex system that may be balanced in the future as has been done in the past.

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