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Linked hydrologic and social systems that support resilience of traditional irrigation communities

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Abstract. Southwestern US irrigated landscapes are facing upheaval due to water scarcity and land use conversion associated with climate change, population growth, and changing economics. In the traditionally irrigated valleys of northern New Mexico, these stresses, as well as instances of community longevity in the face of these stresses, are apparent. Human systems have interacted with hydrologic processes over the last 400 years in river-fed irrigated valleys to create linked systems. In this study, we ask if concurrent data from multiple disciplines could show that human-adapted hydrologic and socioeconomic systems have created conditions for resilience. Various types of resiliencies are evident in the communities. Traditional local knowledge about the hydrosocial cycle of community water management and ability to adopt new water management practices is a key response to disturbances such as low water supply from drought. Livestock producers have retained their irrigated land by adapting: changing from sheep to cattle and securing income from outside their livestock operations. Labor-intensive crops decreased as off-farm employment opportunities became available. Hydrologic resilience of the system can be affected by both human and natural elements. We find, for example, that there are multiple hydrologic benefits of traditional irrigation system water seepage: it recharges the groundwater that recharges rivers, supports threatened biodiversity by maintaining riparian vegetation, and ameliorates impacts of climate change by prolonging streamflow hydrographs. Human decisions to transfer water out of agriculture or change irrigation management, as well as natural changes such as long-term drought or climate change, can result in reduced seepage and the benefits it provides. We have worked with the communities to translate the multidisciplinary dimensions of these systems into a common language of causal loop diagrams, which form the basis for modeling future scenarios to identify thresholds and tipping points of sustainability. Early indications are that these systems, though not immune to upheaval, have astonishing resilience.

1 Introduction

In arid regions around the world, traditional irrigation systems have evolved to maintain community stability despite conditions of prolonged drought and climate variability. In the upper Rio Grande of the United States, *acequia* is the Spanish word for both the physical irrigation works and the water management institutions, governed by users who divert water from rivers and streams dependent on mountain snowpack in the uplands bioregion of north-central New Mexico and southern Colorado. The word acequia is originally

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derived from Arabic *as-sāqiya*, meaning a water conduit or irrigation canal. Transplanted to the New World from Iberia some 4 centuries ago, these community irrigation systems have developed complex self-maintaining interactions between culture and nature that enable drought survival while providing many other cultural, ecosystem, and economic benefits. Many of these benefits are tied to the connections between landscape and community. At the heart of the system, water from the river is diverted onto fields for crops, into ponds for animals, and across valleys supporting riparian vegetation. Grazing and wildlife on the upper watershed rely on forest and rangeland plant communities, the management of which determines runoff to the valley below. Community dynamics that use the valley and watershed for livelihoods determine water distribution that impacts the hydrologic cycle. Importantly, water that seeps from acequias and fields recharges groundwater that in turn provides river flow for downstream users (Fernald et al., 2010).

Starting in 1598, caravans of Hispano settlers and Mexican Indian allies traveled the Camino Real de Tierra Adentro heading north from Mexico City, traversed the Jornada del Muerto north of El Paso, Texas, and finally reached the Ohkay Owingeh Pueblo, north of Santa Fe, New Mexico at the confluence of the Rio Grande and the Rio Chama. Here, they set out to establish agricultural colonies in this northern frontier of New Spain in the search for perennial streams of water fed by snowpacks in the alpine sierras to the north. The colonists knew that in a desert environment there could be no irrigation without a snowpack, a natural system reservoir that accumulates and holds water during the winter months until the rising temperatures release the spring runoff needed to water crops and fields in the valley bottomlands.

As the first public works projects, the settlers diverted streams by constructing diversion dams and then hand dug acequia irrigation canals, on one or both banks, without the benefit of modern surveying equipment. These engineering works were of local physical design in order to operate as gravity flow systems, following the contours of the land with the goal of extending the boundaries of irrigation to the maximum extent before returning the canal back to the river. Due to variations in local topography, the design of each ditch system was unique, always tailored to local conditions and natural features in the landscape. This human engineering design, coupled with its associated social configuration, was specifically located and embedded in the hydrologic system. Acequias diverted and used surface water only when available and therefore made periodic adjustments dependent on water supply stored as snowpack in the upper watershed. Water management practices and operating procedures were adopted in response to natural system conditions during spring runoff, season to season, and over time these repeated adjustments produced a distinctive, community-based hydrosocial cycle.

Out of necessity, and as a potential contributor to the success of each system, the community of irrigators did not adhere to a prescribed set of regulations from a central authority; instead they negotiated institutional arrangements among the collective, operational rules that were specific to the water delivery requirements of the shared canal and its laterals. The taking of water by a collective enterprise carried forward into the local customs and traditions for water distribution and the operation and maintenance of the irrigation works, including repairs at the diversion structure in the river when needed and the annual rituals of ditch cleaning during early spring, just before the expected runoff season. This self-organized enterprise wedded the irrigators into a community system of water management that bonded them and formed a hydraulic society: a culture of water based on shared norms and mutualism. Rules for sharing evolved into a set of customary practices based on knowledge of the land, watershed, and water supply variability.

Today, these traditional communities are facing new socioeconomic and natural resource pressures that might impair their ability to function as originally designed. Like their counterparts elsewhere in the world, unpredictable and/or limited water supplies are a common challenge faced by traditional irrigation systems that depend on surface water and gravity flow technologies. Under conditions of warming temperatures and reduced snow storage during winter months, river flow is expected to decrease and snowmelt runoff has already begun to arrive earlier in the spring, trends that are expected to exacerbate water scarcity in the western United States (Barnett et al., 2008). Among other threats that acequias are facing today, most are directly or indirectly related to population growth and urban area expansion (Cox and Ross, 2011; Ortiz et al., 2007; Rivera, 1998).

In the face of these threats, we hypothesize that these acequia communities persevere by connecting variable hydrologic systems with adaptable human systems. These connections center upon the acequia itself, the physical structure to deliver water from river to field, and the human system to manage the water delivery and use (Fig. 1). We posit that the hydrology cannot be understood without the human connection and the human dynamic cannot be characterized without the hydrology, and the linkages are a source of continuity and longevity.

The goals of this study are (1) to connect human and natural systems using real data that cross over the intersecting disciplines, showing sustainability and adaptive capacity or nonsustainability and tipping points, and (2) identify resiliencies tied to hydrosocial changes that can be characterized only by including the multiple interacting disciplines of the hydrologic and human systems. For expected hydrosocial changes there are resident resiliencies that we measure and document. The system is complex and challenging to assess, highlighting the need for an interdisciplinary approach. Our intention is to show background history leading to the current situation and also examine the features that could impact resilience in the future. We try to identify the basic processes and the resulting impacts.

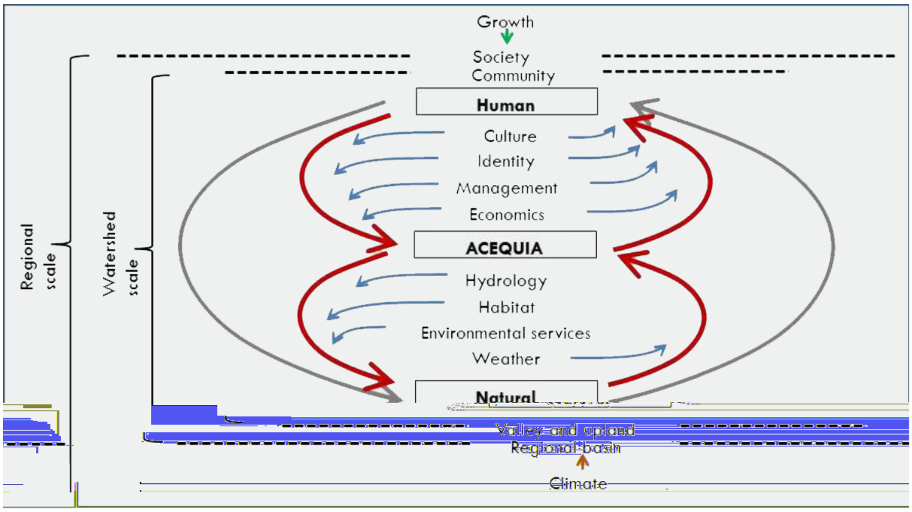


Figure 1. Acequia irrigation centered connections of human and natural systems (Fernald et al., 2012).

2 Resilience due to irrigation seepage

Acequia systems have multiple hydrologic benefits that accentuate resilience. Broadly speaking, the human system of acequia irrigation ditches impacts hydrologic processes by increasing water distribution across the irrigated landscape. Seepage from ditches and fields recharges groundwater, which in turn provides return flow to rivers. At the regional scale, return flow to the rivers delays the runoff hydrograph peak from the spring runoff period to later in the year. The hydrology of these rivers and valleys cannot be fully understood without including the human-created irrigation system. Recharge of aquifers for local groundwater use and downstream return flow benefits is an important aspect of the resiliency discussed below. Acequia seepage support of riparian areas that benefit habitat and biodiversity is another aspect of natural system resilience buttressed by human irrigation systems. These hydrologic and riparian habitat functions of acequia seepage are discussed in additional detail below.

2.1 Ditch and field seepage, groundwater recharge, and river return flow

In northern New Mexico, as in many areas of the southwestern United States and drylands worldwide, snowmelt runoff is the main source of streamflow during spring and summer, and agriculture is largely confined to narrow, irrigated floodplain valleys. In many of these agricultural valleys, river water is gravity-driven into irrigation canals (acequias) that run along the valley, where water is either diverted into smaller irrigation canals or applied directly to crop fields in the form of flood or furrow irrigation (Fernald et al., 2010). We studied water and communities of northern New Mexico (Fig. 2).

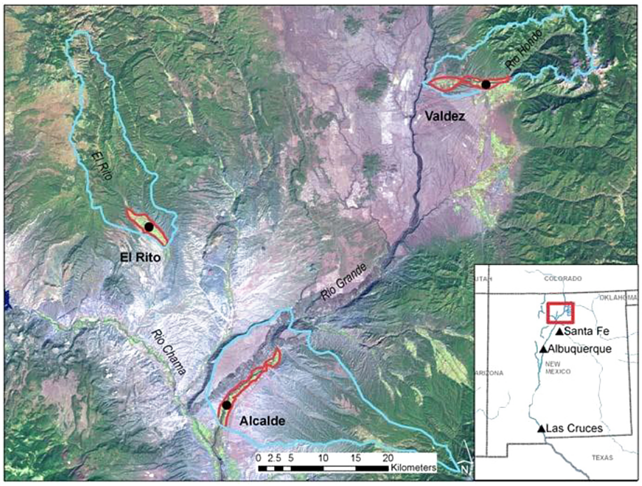


Figure 2. Northern New Mexico acequia study communities (black dots), their associated irrigated valleys (red lines), and contributing watersheds (blue lines) (Fernald et al., 2012).

Farming on the alluvial floodplains is dependent on the connectivity between surface water and shallow groundwater, particularly in the forms of precipitation, runoff, and infiltration processes in the upper watershed and their linkages with streamflow, irrigation, and aquifer recharge in the lower valleys. Results from our combined intensive field monitoring and modeling in communities of northern New Mexico indicate that there is a strong hydrologic connectivity between snowmelt-driven runoff in the headwaters and recharge of the shallow aquifer in the valleys, mainly driven by the use of traditional irrigation systems (Ochoa et al., 2013a). Figure 3 presents results from one of our study sites, illustrating that during the irrigation season (April–October), shallow groundwater levels rise in response to irri-

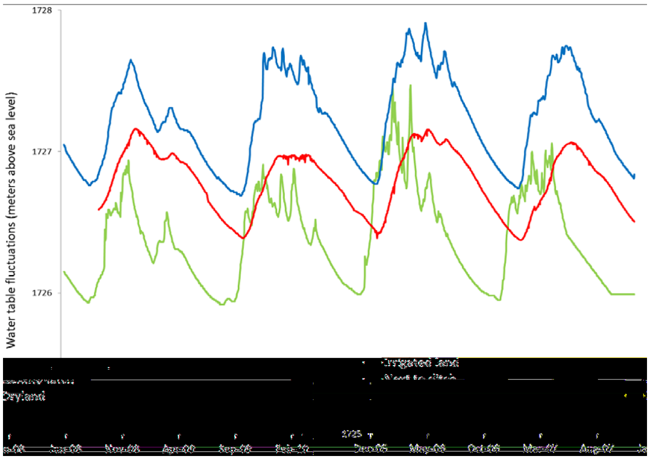


Figure 3. Seasonal water table fluctuations in response to irrigation inputs in one transect of wells in an acequia-irrigated agricultural valley in northern New Mexico.

gation percolation and canal seepage. Then in the late season, without irrigation, the river acts as a drain and starts receiving delayed return flow from groundwater that was temporarily stored in the shallow aquifer during the irrigation season. Also, similar patterns in seasonal shallow aquifer recharge have been observed in wells located in dry land at distances of about 1 km from the main irrigation canal and from any irrigated fields (Ochoa et al., 2013b). Conservation of this seasonal aquifer recharge provides several ecosystem functions including water quality enhancement, riparian habitat support, and river connection to the groundwater. It also supports important economic and ecological functions downstream through temporary storage and release processes. Return flow to rivers from groundwater ameliorates the impacts of climate change by retransmitting to later in the year those snowmelt hydrographs that are earlier and shorter due to increasing hydrographs (Fernald et al., 2010).

The hydrologic connectivity between upland water sources and irrigated valleys through the shallow groundwater system can be important for understanding the hydrologic resilience of agroecosystems in the face of climate variability. Human-induced changes (e.g., changes in land use or in technology) and natural processes (e.g., severe drought) can modify the spatial and temporal patterns of hydrologic connectivity in a given landscape. For instance, a significant change in land use from agricultural to residential and/or a big shift in irrigation technology that favors drip irrigation over the traditional use of flood may severely affect the recharge of the local aquifer. Irrigation efficiency at the farm scale can lead to increased crop yields and less seepage past the plant rooting zone. Flood irrigation is used because it is inexpensive and traditional. Seepage is an unintentional byproduct of the flood irrigation. The seepage, groundwater recharge, and delayed return flow back to the river support important economic and ecological functions.

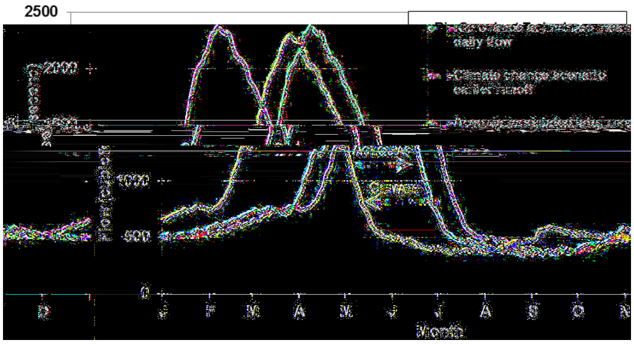


Figure 4. At the regional scale, acequia surface water–groundwater interactions may ameliorate effects of climate change by delaying the spring runoff that is projected to be earlier in the year.

Climate warming and changes in the quantity and temporal frequency of precipitation threaten the accumulation of snow, timing of melt, and thus the timely delivery of water for irrigation. In a case study of the effects of climate warming on streamflow in the El Rito watershed, it was determined that warmer temperatures predicted by the end of the 21st Century are likely to cause peak runoff to occur approximately 15 days earlier than it now does.

Although peak streamflow is predicted to occur earlier in the year and the volume of water delivered during peak streamflow is potentially greater than historical years, the connectivity between snowmelt-driven runoff and aquifer recharge provided by acequia flood irrigation provides a means for mitigating the potential for flooding and/or loss of water. The temporary storage and release of water provided by flood irrigation is important locally for ensuring water supply longevity through the growing season within the acequia valley itself. The effects of runoff modulation by acequias are also anticipated to extend beyond the local scale to the regional scale as illustrated by a conceptual diagram of the Embudo Station stream gauge hydrograph on the Rio Grande (Fig. 4).

2.2 Climate change effects on biodiversity and related ecosystem services

Biological diversity is threatened by land use change, yet acequia system contributions of water maintain riparian areas and so help mitigate the loss of these habitats in adjacent landscapes. Acequia irrigation provides much of the water for habitat in our semiarid study area and the climate changes that impact water and agriculture may negatively impact ecosystem health. Biodiversity and ecosystem services can be used to provide perspective on the ecological integrity or health of an ecosystem. A measure often used for biodiversity, and now for ecosystem services, is species richness. This is not the only measure, but it is one that can be calculated across time and space at a reasonable cost. Recent literature has identified that acequias benefit biodiversity and provide ecosystem services. To measure this impact we used biodiversity metrics created from a species habitat model (Boykin et al., 2007). These metrics reflect ecosystem services directly or components of biodiversity (Boykin et al., 2013). For example, the ecosystem services concept can be connected to metrics such as bird richness. There is an economy tied to avid bird-watchers who travel to view species. These people often go to species-rich areas to see a wide variety of avifauna.

We looked at the northern Rio Grande watershed. The regional focus provided the context for further analysis of biodiversity metrics and ecosystem services within the smaller acequia study areas. These perspectives allow us to understand where the most species-rich areas are regionally. We can also start to understand how broadscale land use changes may affect the finer-scaled acequia areas and vice versa using land use scenarios consistent with the Intergovernmental Panel on Climate Change (IPCC) global greenhouse gas emission storylines (Bierwagen et al., 2010). All future land use scenarios predicted losses in bird richness in each richness class. Species richness losses ranged from greater than 24 % for high development scenarios to less than 4.4 % for low development scenarios. A large percentage of habitat, including acequia-irrigated fields and riparian areas that support species diversity, are lost to urban development. The scenarios driven by economic forces lose a large percentage of habitat, while those driven by environmental forces lose the least amount of habitat. These data for our acequia community study region show that water and climate alone are not likely future determinants of ecosystem health. These results indicate that minimizing habitat loss from expanding urban footprints along with maximizing riparian habitat, is likely to reduce biodiversity loss along river corridors.

3 Place-based adaptation to changing land use and economics

If communities can stay connected to the acequia landscape, grazing, farming, economics, and land use changes allow them to adapt and survive. Region-wide livestock numbers have fallen somewhat since the mid-1980s, yet strong links between livestock raising and irrigated farming contribute to the cohesion of acequia communities. Streamflow is highly variable and the recent past includes very dry years, but added income independent of farming provides a coping strategy to weather periods of drought. Acequia farming has lost its role as a main provider of food for the community, but regional urban area demand for local food along with alternative crop availability to acequia communities provides options for adaptive responses. Drought and climate change threaten continued crop production, but a history of adaptations as well as maintenance of acequia infrastructure and farm plot arrangements indicates flexibility to transform and meet future challenges.

3.1 Historical changes in settlement morphology and agriculture at county and local community levels

In the future, acequia communities may need to respond to water demands in urban centers and drought through adaptation of land use and agricultural practices at the community scale. In order to understand the resilience and adaptive capacity of acequia-based community systems, we focused research on how acequia settlements have adapted over time in response to economic and environmental factors. The construction of Los Alamos National Laboratory in 1943 transformed the economy from agropastoral subsistence farming to wage-based off-farm employment. For Rio Arriba County in 1935, there were 3500 farms documented, 1400 of which were between 3 and 9 acres, and another 600 farms ranging from 10 to 19 acres accounting for 57 % of the farms in that year (USDC/USDA, 2014). In subsequent decades, agricultural parcels would increase in size; 1200 farms were reported in 1964, 380 of which were between 1 and 9 acres in size, and another 400 farms were classified as having from 10 to 49 acres, making up 65 % of the farms in that year (USDC/USDA, 2014). In 2007, of the nearly 1400 farms reported to the US Census, the range in parcel size remained consistent with that of the 1960s (Fig. 5). The overall decline in small-size farms from 1935 to 1964 suggests a shift in the agricultural system from a subsistence form of agriculture to one of supplemental income.

At the county scale, there has also been a major transformation from a sheep economy to a cattle-based economy, which may have also resulted in a change in cropping patterns in acequia communities over the last 75 years. In the 1930s, sheep and chickens significantly outranked cattle numbers. However, by 2007 cattle numbers in Rio Arriba County far exceeded any other livestock type (Fig. 6).

At the community scale, findings on historical land use change in Alcalde resulted in a decrease of total acreage of field crops from 84.5 to 30 acres, urban development into the irrigated farm land increased 42.3 acres, and average agricultural parcel size decreased from 3.6 to 1.9 acres (Fig. 7). Also, the channelization of the Rio Grande increased the bosque (riparian) vegetation in the study area by approximately 14.9 acres during the same period. Initial findings from mapping community scale morphology changes over the past 75 years revealed an increase in farm plot size, a dispersed settlement pattern, and less crop diversity. In addition our findings reveal a restricted channelized riparian condition along a portion of Alcalde (Fig. 8).

3.2 Upland grazing and recent trends in livestock inventories

Despite longer term changes in the agricultural landscape of the valleys, livestock raising and irrigation farming continue to be tightly intertwined in traditional Hispanic rural communities of northern New Mexico. Owning livestock continues

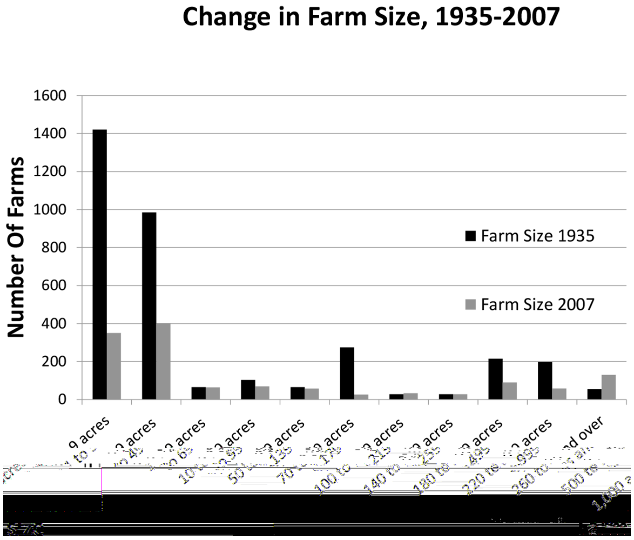


Figure 5. Agricultural parcel size for Rio Arriba County in 1935 and 2007 (NASS, 2012; USDC/USDA, 2014).

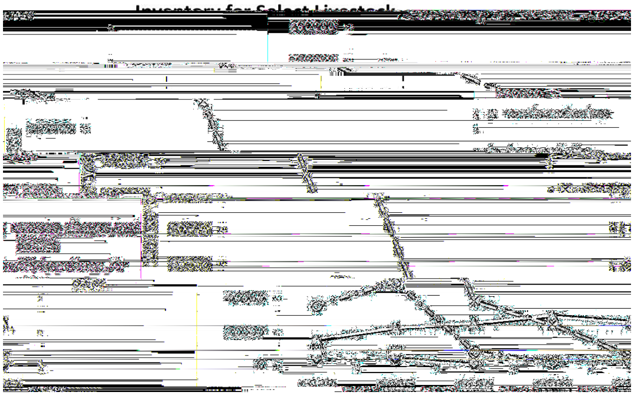


Figure 6. Inventory of livestock 1930–2007, Rio Arriba County (NASS, 2012; USDC/USDA, 2014).

to be vital to acequia community families; it is a way of reconnecting to their heritage (Eastman and Gray, 1987) and "an essential component of [their] historic persistence and self-reliance" (Cox, 2010; p. 65). Livestock raising, however, is only possible if access to uplands surrounding irrigated valleys is available for grazing during the growing season. Spanish deposition of farming lands included grazing rights on adjoining uplands (now regulated by the federal government), which constitutes a testament to the historical importance ascribed to livestock raising as a means of community financial stability (E. Gomez, personal communication, 2012).

Region-wide sheep and goat grazing permits on upland forests administered by the United States Forest Service were reduced dramatically beginning in the early 1900s (Fig. 9). The reduction in cattle grazing permits on forested uplands has become more pronounced since the mid-1980s (Fig. 9).

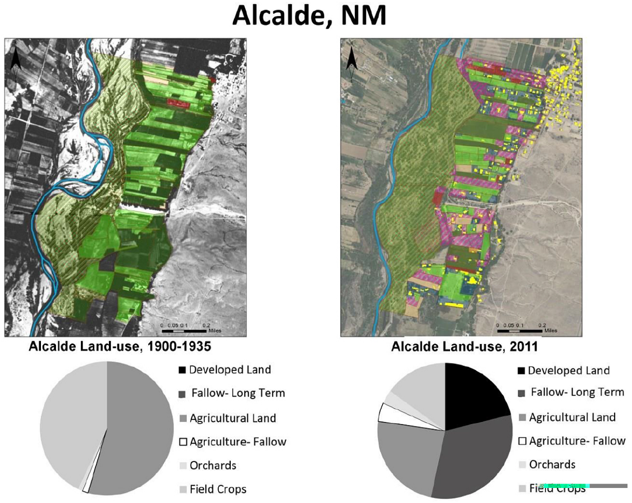


Figure 7. Community level changes in land use for Alcalde (Earth Data Analysis Center, 2010; Rio Arriba County Assessor's Office, 2013).

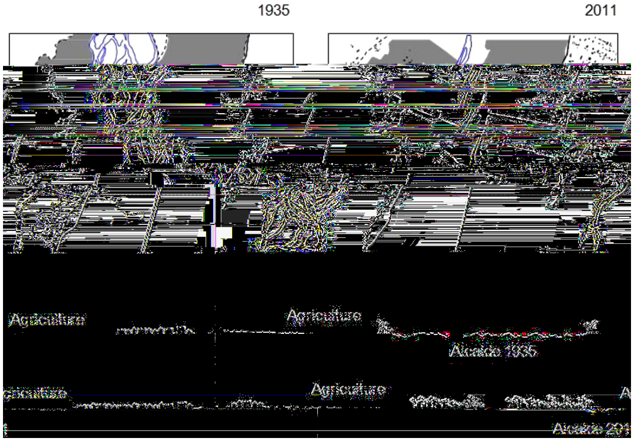


Figure 8. Changes in landscape morphology of the community of Alcalde (Earth Data Analysis Center, 2010; Rio Arriba County Assessor's Office, 2013).

These changes have been mirrored by trends in livestock inventories in the counties surrounding our study sites (Fig. 6). Although this phenomenon varies locally (Raish and McSweeney, 2003; Cox, 2010; Lopez, 2014), and even though acequia communities have the ability to adapt to change, these trends could point to the weakening of an activity that has historically provided a natural link between valleys and uplands and has contributed to the cohesion of acequia communities (Cox, 2010; E. Gomez, personal communication, 2012).

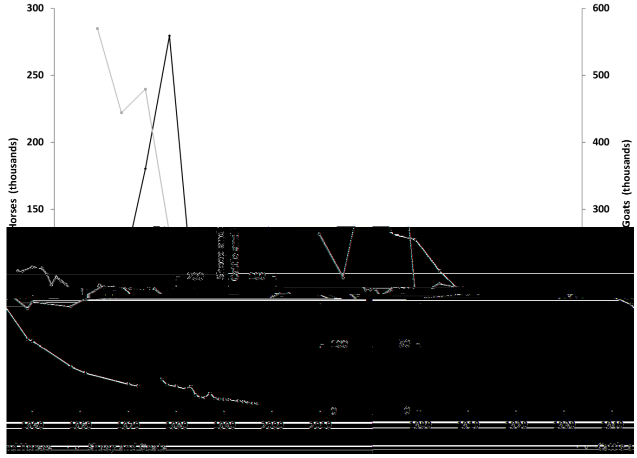


Figure 9. Grazing permits on national forests of New Mexico granted by the United States Forest Service from 1909 to 1997 (Source: USDA – Forest Service, 1991 and 1998).

3.3 Acequia resilience in the face of economic and land use changes

The land use change in Alcalde has been similarly documented for other communities in Rio Arriba County. Since WWII, acequia communities moved away from small tract subsistence agriculture to an agricultural system based on cattle production in order to maintain the irrigation system despite economic shifts in the region. The move from field crop diversity to pasture forages for livestock feed provided economic gain for farmers to participate in the post-WWII wage economy while maintaining irrigable acequia farmland. The challenge today of prolonged drought and climate change coupled with the reduction of grazing animal units on US forest land will increase pressure on the grazing system. However, acequia communities have the opportunity to develop strategies for adapting the existing land use configuration of irrigable farmland into a system capable of dealing with the potential impacts of prolonged drought and climate variability. Possible strategies include value added crop production, use of drip irrigation, and the use of alternative agricultural technology. The pre-WWII acequia community was resilient in that the farmers promoted crop diversity, utilized low energy inputs from farm machinery, and maintained sustainable practices on small parcel farms. Overall, land use conditions in Alcalde have been altered, but the acequia infrastructure and farm plot arrangements have endured and have adapted over time, indicators of resilience with flexibility to transform and meet climatic and other challenges in the future.

3.4 Economic trends and adaptation opportunities analyzed in terms of community balance sheets

The community capacity for resilience depends on preparedness and adaptation through accumulation of various types of human, financial, natural resource, and social–cultural assets. These assets act broadly as indicators of community wealth and strength, representing a type of community balance sheet. Each asset category is strengthened or diminished in a community balance sheet by changes in the status or performance of a community's economic, demographic, and environmental systems. For example, changes in regional net income from employment and productivity will change the community's aggregate financial wealth. As another example, natural and environmental resources, including fertile agricultural crop, grazing and forest lands, and water resources, are seen as contributing to the essential character of an acequia community. Many of these resource assets are renewable and their quantity and quality are subject to fluctuation and change, depending on variable factors such as climate, natural events and cycles, rates of extraction and transformation (including conversion of agricultural land to development), and changes in regulatory policy that can erode or strengthen the asset value by affecting resource access and use.

Mayagoitia et al. (2012) found that acequia residents exhibit a strong identity with and affinity for the local land, water, and cultural resources. A survey of acequia irrigators in northern New Mexico and in-person interviews asked irrigators about both economic and cultural perceptions and their views of acequia strengths and challenges. A particular survey focused on the current state of preparedness to endure stress from adverse economic conditions, continued drought (under climate change), and regional population growth. 77 percent of respondents cited connectivity and mutual relationships as factors contributing most to the acequia community's preparedness (i.e., adaptive capacity) (Fig. 10).

The concept of a community balance sheet also conforms well to notions of sustainable development as defined by the Brundtland Commission as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987). Long-term sustainability and resilience would be consistent with a community's overall "balance sheet" remaining healthy and resistive to excessive degradation and long-term net loss. Although reductions in non-renewable resource capital are expected, it would also be consistent to expect an associated accretion in economic capital as a result of the transformation of natural capital into economic capital. For example, for a mining community to remain economically viable in the long term as mineral resources are depleted, its economy must invest in transitional economic development. Otherwise it would risk long-term economic decline and consequential losses and erosion in the other categories

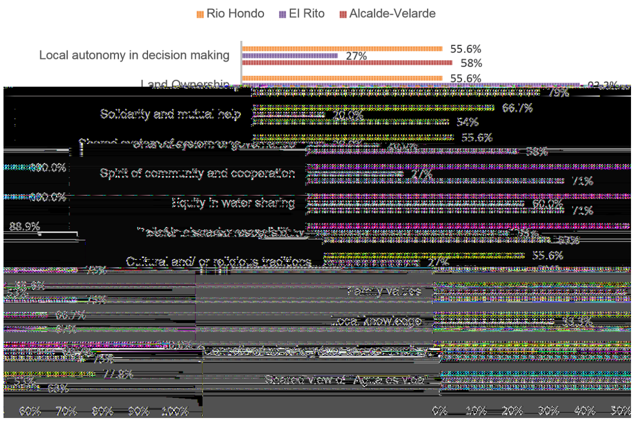


Figure 10. Acequia characteristics perceived to "best contribute" to acequia adaptive capacity, past adaption, and resilience.

of community capital, including population and sociocultural resources.

In the 42 years preceding 2011 there was a steady transformation of the employment base for the communities in Taos and Rio Arriba Counties, the two counties in Northern New Mexico with the largest concentrations of acequia communities. As Fig. 11 shows, these communities are both transforming from primary extractive and resource-based economies to service, professional, and government-service centered economies. Between the years 1970 and 2000 the services sector shares have risen from about 50 % to nearly 70 % in Taos County and similarly from about 40 % to over 50 % in Rio Arriba County. Agricultural employment has remained relatively flat at approximately 4 % for Taos and 8 % for Rio Arriba. These trends suggest a greater dependence on regional employment centers, greater off-farm income support, and higher commuting rates. Such regionalization can affect community "balance-sheets" in several, sometimes offsetting, ways. For example, diversification from traditional extractive economic activities can strengthen incomes and raise financial wealth and capacity; however, this may come at some cost to sociocultural strength and well-being, with less time and commitment to community-centered activities and relationships.

Trends and changes in farm income and the agricultural economy of the acequia region, coupled with changes and variations in the water supply situation, are shown in Fig. 12. Roughly consistent with the long-term steady employment picture in farming and ranching, there does not appear to be a strong positive or negative trend in farm and ranch incomes over this period. However, there is a relatively high degree of income variability that is largely independent of regional water supply conditions.

4 Sociocultural perspectives to understand resilience

In the acequia culture of the historic Rio Arriba bioregion (northern Rio Grande), attachment to place is strongly held by multiple generations of irrigators who have long historical connection to their landholdings. This sense of place is exhibited in many ways that promote resilience related to acequias and water management.

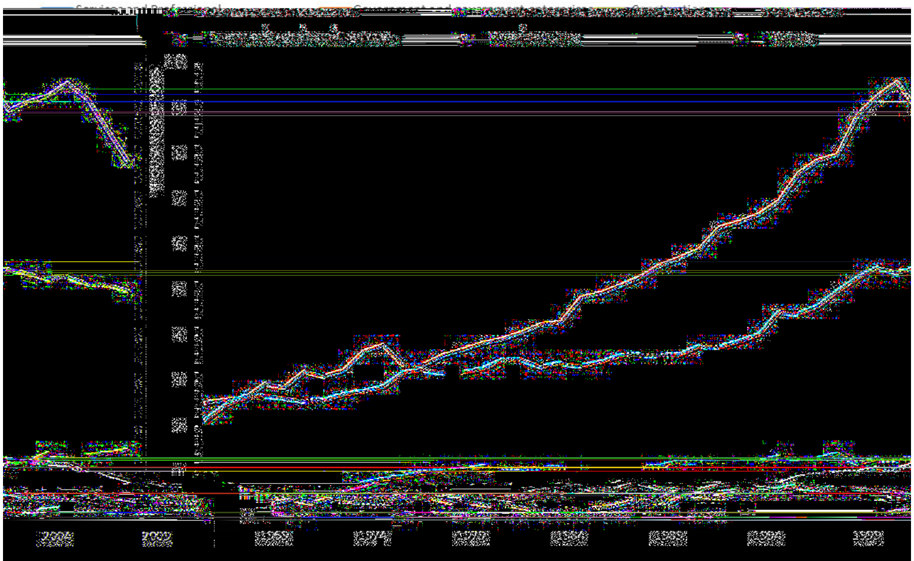
4.1 Sociocultural knowledge and the hydrosocial cycle

As with other forms of traditional agriculture around the world, acequia irrigation in the Rio Arriba is knowledge intensive in terms of understanding and responding to the local hydrological and environmental conditions upon which the system depends. The complete system is carried collectively in the local knowledge of the irrigators, particularly with regard to the distinctive micro-region of their community: soils, climate conditions, crops, and water requirements for every niche suitable for agriculture (Glick, 2006). The mutuality of the irrigators derives from the values encoded in the operational rules of water sharing, namely equity, justice, and local control (Maass, 1998). This knowledge is derived from and expressed in practical, experiential terms and, after repeated cycles, is embedded in the culture and passed on to new generations as part of the social and institutional memory of the community (Folke et al., 2003).

4.2 Acequia resilience: the role of the New Mexico Acequia Association

The New Mexico Acequia Association (NMAA) conducted an assessment survey in 2008 (before the current research project reported here) to document the concerns of its membership in order to generate effective governance program planning and strategies to benefit acequias. Topic areas included needs, crop and water management trends, infrastructure conditions, and overall health of acequias. The survey was distributed to acequia officers as the targeted group due to their knowledge of their local acequias. In some cases, individual member irrigators completed the surveys when the governing body was not available. A synopsis report by the NMAA highlighted the survey responses in the two example charts below (Fig. 13a and b). The results show that the cited values are of high importance while low community participation, few members irrigating their crops or raising livestock, and problems with the irrigation works were noted as important challenges. The NMAA took action to address these needs and concerns by way of programs, workshops, and leadership development projects intended to assist acequias in recruiting, train the next generation of acequia managers, strengthen acequia administration, and recruit community leaders to take active roles in policy development. With respect to infrastructure repairs, the NMAA holds workshops

(a) Taos County



(b) Rio Arriba County

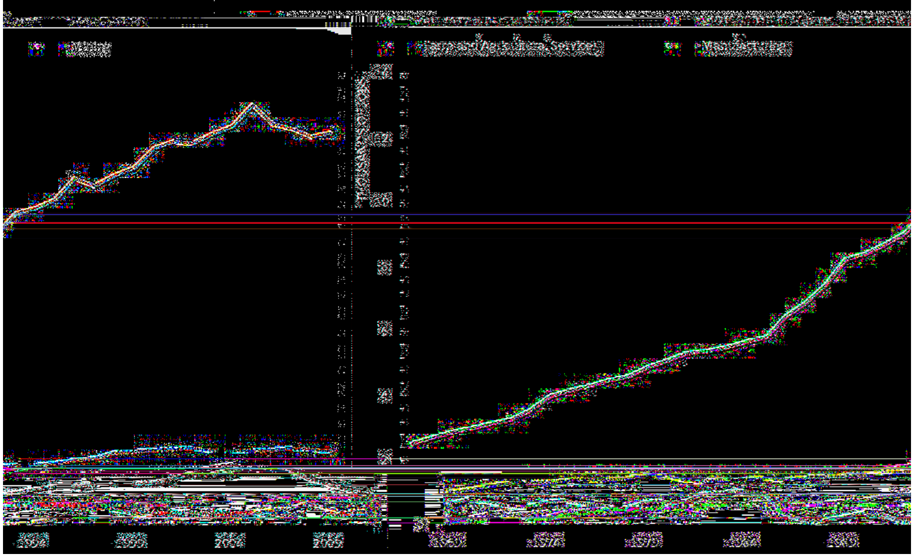


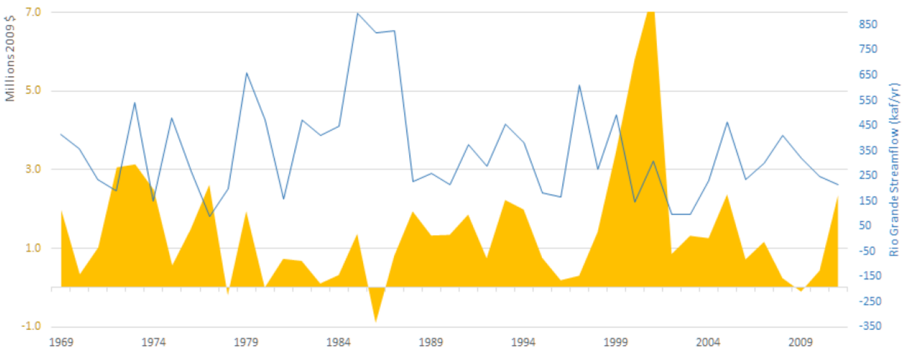
Figure 11. Employment shares and trends by sector in Taos and Rio Arriba Counties, New Mexico (US Bureau of Economic Analysis, 2013a).

on how member acequias can qualify for the ditch rehabilitation financing available from state and federal agencies.

4.3 Acequia resilience: views of officials and irrigators

Traditional local knowledge about the hydrosocial cycle of acequia operations is a key factor in acequia resilience when the irrigators are confronted with disturbances, unexpected events, or changing climate that affects water supply. Adaptability in times of stressors is self-evident by the fact that acequias as human and social institutions still operate and have not disappeared even after political administration under four sovereigns and their shifting water law regimes: (1) Spanish colonial, (2) Mexican period, (3) US Territorial, and (4) New Mexico statehood in 1912. Focus group sessions with acequia officials and irrigators, along with supporting evidence from similar case studies in other arid regions of the world, suggest a number of intriguing propositions with regard to resilience factors of acequia irrigation systems:

(a) Taos County, New Mexico



(b) Rio Arriba County, New Mexico

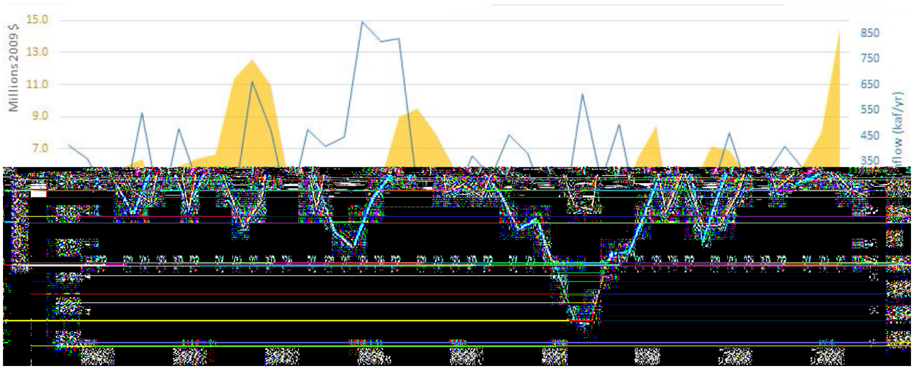


Figure 12. Trends and changes in agricultural incomes (orange areas) and streamflow (blue lines) for Taos and Rio Arriba Counties in New Mexico (US Bureau of Economic Analysis, 2013b; US Geological Survey, 2013).

1. Attachment to land and place develop a collective identity with a set of shared values and cultural norms, producing what can be called an "acequia imaginary".
2. Mutual networks and social density result in cohesion and solidarity of community when confronted with change or stressors from outside the community.
3. Leadership by key individuals such as the acequia officers maintains and retains the customary rules and local management practices of the system.
4. Social memory embedded in the culture instructs acequia leaders and irrigators on how to respond to and withstand disturbances or year-to-year changes.
5. Ecological knowledge of local conditions and environment is carried collectively and transmitted to new generations.
6. Local control of resources increases the capacity to adapt in times of scarcity such as cycles of prolonged drought.
7. Autonomy of decision-making structure and discretionary authority permit rapid adjustments in operational rules and practices when warranted by changing or unexpected conditions.

5 Discussion

5.1 Identifying essential variables to model future scenarios

Information gathered from the local communities was placed into the framework of a causal loop diagram. The causal loop diagram is a tool to represent interacting variables of a system, and it is a precursor to simulation modeling. Causal loops were also created for hydrology, economic, and environmental variables as discussed in Fernald et al. (2012). Community members were invited to a workshop with researchers to refine the causal loop diagrams based on their own understanding. The data that researchers collected were used to identify and assess the key variables among all of those identified in a collaborative community water research process (Guldan et al., 2013).

Ongoing system dynamics modeling based on the causal loop diagrams will be used to turn narratives into future scenarios that identify thresholds and tipping points of sustainability (Fernald et al., 2012). Our ongoing approach is to

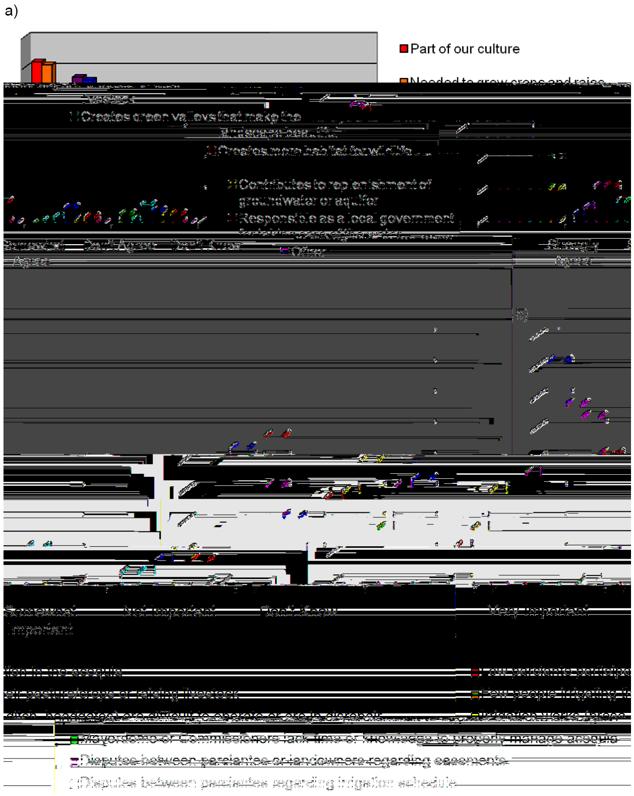


Figure 13. (a) Responses to the question "what is your opinion about the following statements about the importance of your acequia to your community?" and **(b)** Responses to the question "what do you believe are the important challenges within your acequia?"

distill out the essential variables in the system using our field data from the multiple disciplines and incorporating them into a simulation model. When we put together the causal loop diagrams for all disciplines and work with community members, key variables emerge as shown in the essential causal loop diagram (Fig. 14).

In order to identify resilience, sustainability, thresholds, tipping points, and future directions for hydrologic and community health, our ongoing work is developing a model that brings together all scenarios to help identify higher levels of interaction than are obtainable with disciplinary approaches.

We will use cross-cutting scenarios within system dynamics modeling to test tipping point hypotheses. System dynamics modeling uses stocks of key variables and parameterized flows between them to recreate the systems under consideration. In our case, we will bring together the multiple threads and model scenarios based on our field data from the multiple disciplines. We will establish a dynamic hypothesis specific to the system dynamics modeling exercise. We will iteratively put the hypothesis in front of the different researchers as the model is developed based on the causal loop diagrams that were drawn with community help. Then the model itself will be tested and validated with community members and researchers.

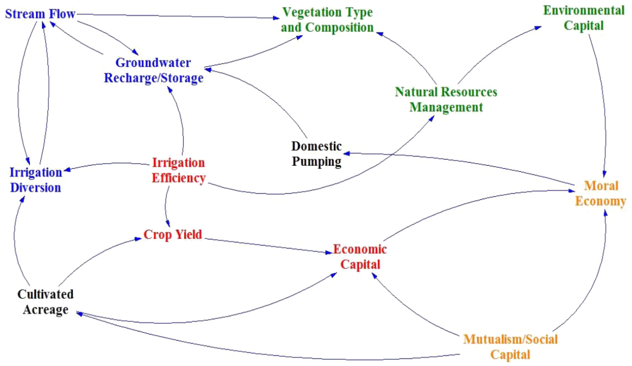


Figure 14. Essential causal loop diagram with key variables for modeling. Black variables are critical elements integrating across multiple subsystems, while colors are primary to individual disciplines.

5.2 Example model development

The causal loop diagrams that we have created in collaboration with the communities are allowing us to model scenarios of interacting water, agriculture, society, and economics. We present here a theoretical case of model development showing interacting prices, crops, and water use. Fig. 14 shows a number of variables. We select two here, cultivated acreage and crop yield, that relate closely to crop production (irrigated agriculture) for the Acequia de Alcalde, an acequia along the main stem of the Rio Grande.

Each of these two variables is affected by more variables than the essential causal loop diagram indicates (see Fernald et al., 2012), for example labor availability, crop price, and market. Perennial forages and tree fruit orchards are the two primary, yet very different, crop types that make up the majority of the irrigated land that the Acequia de Alcalde provides water for. Currently, there are on the order of 50 acres of tree fruit orchards and 620 acres of hay forage (Table 1).

The proportion of irrigated acres in orchards vs. forage crops can potentially be influenced by changes to various factors/drivers. Decrease in availability of farm labor could lead to a decline in orchard acres, whereas an increased demand for local fresh food might convert some forage fields into orchards. Climate change may exacerbate the common problem of tree fruit crop loss due to late spring frosts. As has been the trend, any factor that decreases acreage of orchard crops may increase forage acreage or result in less overall cultivated acres.

A scenario of decreased irrigation water supply, such as with a long-term drought, might shift acres from forages to apples or other specialty or higher value crops that can more easily be adapted to micro-sprinkler or drip irrigation (a difficult resilience strategy for producers only having equipment

Table 1. Approximate cultivated acreage (D. Archuleta, personal communication, 2012), yield, and gross revenue ranges (Forage, Currier et al., 1995; Lauriault et al., 2004; Apple/Orchard crops, S. Yao, personal communication, 2012) of two crops and potential effects from various factors (Acequia de Alcalde).

Cultivated area	×	Yield/area	=	Total yield	Gross revenue
Forage 620 acres		4–6 tons acre^{-1}		2500–3700 tons	0.5–1 million USD
Apple/orchard crops 50 acres		6–13 tons acre^{-1}		300–650 tons	0.3–0.65 million USD*

* Through direct marketing at roadside stands or farmers markets, apples and other orchard crops can potentially produce significantly higher revenues per acre than indicated.

and experience with forage crops). Forage producers might also shift to forages that use less water, but that would also yield less, or a loss in overall cultivated acres may occur as hay fields are left idle.

Cropping patterns could also change due to socioeconomic, policy, and cultural factors, in extreme cases having an effect on the hydrology of the system. For example, grazing restrictions or increased costs of grazing permits in uplands due to policy changes could impact local demand for hay: an increase in demand could occur to meet herd feed needs, or a decrease in demand could occur if herds are reduced, possibly leading to a shift to other crops or idling of acres. The latter could reduce aquifer recharge and groundwater return flow to the river due to lack of seepage and deep percolation (Fernald et al., 2010).

Along many acequias, demand for housing and the associated increase in land prices have often caused pressure to subdivide fields into residential lots. This decrease in irrigated acres has likely reduced seepage and percolation in the system and thus reduced aquifer recharge and groundwater return flow. In the case of one county (Rio Arriba), a resilient response to this has been an ordinance passed several years ago that stipulates agricultural fields be developed in a manner that maintains 70 % as open field, with 30 % allowed for development as cluster housing (Rio Arriba Agricultural Protection and Enhancement Ordinance, adopted 31 January 2002; prepared by the Rio Arriba County Planning and Zoning Department, Rio Arriba County).

Our approach enables a quantification of system connections as illustrated by the grazing example. A preliminary analysis of farmer/rancher surveys and historical records of public land grazing in areas adjoining irrigated valley study sites suggests a tight connection between irrigated hay production and year-to-year variation in upland livestock numbers (Lopez, 2014). Although it is difficult to isolate the influence of hay production from factors such as public land use policies that determine the length of the summer grazing season (and therefore the number of winter feeding days), availability of valley-grown forages appears to be an important driver of livestock herd dynamics in the local farming/ranching communities (Lopez, 2014). Thus, projected changes in snowmelt regimes and irrigation water availability could indirectly affect traditional livestock-raising activities and weaken local economies and ancestral valley upland sociocultural connections.

We have identified resilience as well as susceptibility to change. We contend that multiple lines of evidence enable us to construct meaningful future scenarios to test the limits of these systems. We envision an interacting causal model based on our causal loop diagrams and field evidence that sheds light on the tipping point hypothesis. What will happen, for example, if acequia farmers sell their land, and water is transferred off the land to regional urban centers? Based on the integrated model, we might find that under this scenario farming is reduced, impacting the timing and distribution of flow, reducing seepage and groundwater return flow, reducing riparian function, and reducing river flow in late summer and fall. Reduced farming and grazing result in changing vegetation structure and increased density and cover, which leads to increased wildfire in a warmer future, further exacerbating pressures on grazing and farming. We have shown that these systems adapt and change, but there are also signs that key components of the acequia systems have limits to resilience.

5.3 Integrating elements

Although a more comprehensive integration of elements affecting resilience in acequia systems will be provided upon completion of the system dynamics model (Fernald et al., 2012), we highlight in this section some key hydrosocial interactions that have a bearing on resilience. Seepage from the acequia canals and flooded fields studied recharges the aquifer. This provides resilience for the local community – for farmer and non-farm rural residents alike who rely on either shallow domestic wells or community water systems. Recharged aquifers appear to provide delayed groundwater return flow to the river, providing resilience for the basin as a whole by benefitting downstream irrigators and other users.

A drastic reduction in seepage through wide-spread adoption of practices meant to increase irrigation efficiency at the field scale (e.g., drip irrigation) or a reduction in area under irrigated agriculture due to urbanization or greater movement away from on-farm employment can decrease these resiliencies. On the other hand, practices such as drip irrigation can allow irrigated agriculture to continue if water becomes significantly less available because of long-term drought or climate change. With increasing pressures and policy development to facilitate the transfer of agricultural water to growing cities, drip irrigation in combination with partial lease of irrigation water rights to the cities could provide a trade-off that helps a farmer stay in agriculture. This conversion, on the other hand, would possibly entail a shift from alfalfa pastures to row crops, which would require irrigators to modify their livestock-raising enterprises to adopt off-site winter feeding options.

Whereas urbanization puts pressure on agricultural land and water resources, a certain critical mass of nearby urban consumers can provide demand for local, high-value agricultural products. The high-value products can increase incomes for small-scale acequia farmers, again increasing chances that agriculture continues and seepage benefits continue.

Acequia group leaders discuss the lack of community participation in operating, governing, and maintaining acequias. Our conjecture is that this does impact resilience, but more in terms of community cohesiveness and not so much in terms of hydrologic regimes, because acequias continue to flow. It is interesting to note that although individual acequias may not have the active participation of all irrigators, participation of regional acequia associations at the annual meeting of acequias (*Congreso de las Acequias*) has increased greatly since the meetings began 15 years ago.

Socioeconomic data indicate that in some acequia communities, income is not strongly influenced by regional water supply conditions. This can be viewed in different ways. For example, are acequias not important for the community? Or, because acequias continue to operate regardless of water supply, does this indicate they play a role in or are a measure of community resilience? Survey results (Mayagoitia et al., 2012) indicate acequia residents continue to exhibit strong identity with and affinity for the local land, water, and cultural resources. This cultural aspect, as well as the policy and socioeconomic influences mentioned above, supports a key principle – understanding people and society is critical to understanding the hydrology of a system.

6 Conclusions

Keys to resilience are found in hydrologic and human system connections. Seepage from acequia systems supports a host of hydrologic and riparian resilience functions. Hydrologically, seepage recharges groundwater and provides attenuated return flow to rivers and streams. Riparian areas support most of the biodiversity in these regions. Reduction in water may reduce riparian areas and acequias can provide additional refugia in times of low water. Community cohesion has resilience in the value of attachment to place derived from acequia and local farming culture. Livestock raising contributes to strengthening the economic and social resilience of traditional acequia irrigation communities of northern New Mexico. The ability to grow irrigated forages appears to be critical to the persistence of this well-established agricultural activity. Changes in snowmelt regime and water availability for irrigation could cause further reductions in herd numbers and severely weaken the cohesion of acequia farming communities.

Acequias are resilient because they are in step with the scope and scale of variability in the natural systems. The roots of sustainability are the intricate linkages that have developed over generations, connecting human and hydrologic systems. For example, acequia water is distributed in keeping with the highly variable precipitation of the region. Unlike priority water law that gives the oldest water rights the water in times of scarcity, acequias share the water. In wet times everyone gets more, and in dry times everyone gets less. Irrigated lands were established to match the wet and dry years, with vital lands near the river irrigated in dry years and lands farther from the river added to the irrigated footprint in wet years. Adaptation to semiarid system variability and connection to place are at the heart of an acequia's ability to adapt.

Our data have demonstrated that acequia systems have very high resilience and adaptive capacity but also show susceptibility to major upheaval. Thus shocks to the system such as climate change and land use change that impact water and ties to the land are particularly disruptive. Tipping points may be reached when external drivers push these systems beyond their historic limits. It is widely acknowledged that a regional megadrought in what is now the US southwest pushed Pueblo peoples beyond their capacity to adapt and caused widespread migration and cultural upheaval. Signs of tipping points are showing now in the Taos valley where developers have paved over acequias, blocking downstream users access to water. In 2013, after 10 years of drought, river water was significantly low, and acequia communities were on the verge of filing lawsuits against upstream users until seasonal monsoon rains allowed irrigation to resume. Resilience and tipping points can be propagated both upstream and downstream due to hydrologic connections and trans-basin water movement. Although timely rains occurred in 2013, if droughts of historic depth and duration occur, acequia systems appear vulnerable to upheaval.

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