

# **Acequias of the Southwestern United States:**

## Elements of Resilience in a Coupled Natural and Human System

**AGRICULTURAL EXPERIMENT STATION • RESEARCH REPORT 796**



Compiled by

Adrienne Rosenberg, editor,

and Steven Guldán,

Alexander G. “Sam” Fernald,

and José Rivera,

associate editors



**College of Agricultural, Consumer  
and Environmental Sciences**

New Mexico State University

[aces.nmsu.edu/pubs](http://aces.nmsu.edu/pubs)

# TABLE OF CONTENTS

---

Foreword.....	1
Editor’s preface.....	3
<b>Part 1—Overview</b>	
“Key Concepts for a Multidisciplinary Approach to Acequias” (Sylvia Rodríguez) .....	4
<b>Part 2—Disciplinary Research</b>	
“The Roots of Community in the Northern Rio Grande: Acequia Mutualism, Cultural Endurance, and Resilience” (José A. Rivera) .....	13
“Acequia Ecosystems” (Kenneth G. Boykin, Elizabeth A. Samson, and Guillermo Alvarez).....	21
“Surface Water and Groundwater Interactions in Acequia Systems of Northern New Mexico” (Carlos G. Ochoa, Steve J. Guldán, and Sam Fernald) .....	33
“The Role of Livestock in Supporting Acequia Communities of Northern New Mexico” (Stephanie C. López, Andrés F. Cibils, Lilian Cibils, Ursula R. Smedly, Steve J. Guldán, Sam Fernald, Carlos G. Ochoa, and Kenneth G. Boykin) .....	41
“Perceptions of Drought Preparedness and Adaptation within Acequia Communities” (Brian H. Hurd and Laura Mayagoitia).....	48
<b>Part 3—Interdisciplinary Research and Analysis: Bringing it all together</b>	
“Connection and Integration: A Systems Approach to Exploring Acequia Community Resiliency” (Ben L. Turner and Vincent C. Tidwell) .....	58
“Coupled Natural and Human System Clues to Acequia Resilience” (Sam Fernald, Carlos G. Ochoa, and Steve J. Guldán).....	72
Appendix.....	79
Glossary .....	84
Coauthor bios .....	88

---

(Cover photo by Sam Fernald, NMSU.)

## FOREWORD

**T**he pages that follow offer, in a comprehensive and multidisciplinary manner, strong and tested evidence about the multiple cultural and natural values and environmental, social, and economic services rendered by acequia irrigation systems. The study focuses on New Mexican acequias, but the findings are of worldwide interest.

All around the Earth, community-based flood irrigation systems, owned and managed by self-organized farmers, continue to provide the basis of subsistence to local communities in contexts of scarce or uneven yearly rainfall. A significant group of these communities, stretching from Central Asia to the Philippines, share a common background of agricultural and water knowledge that was forged in the advent of Islam. This knowledge fostered the circulation and merging of the millennial Asian and Mediterranean irrigation cultures with precious inputs from the Indian and Chinese worlds. As a cultural tribute to the ingenuity of the cosmopolitan irrigation agriculture developed in Muslim times, the Spanish, Catalan, Portuguese, and Sicilian languages refer to irrigation channels with the names of *acequia*, *séquia*, *acéquia*, and *saia*, respectively, from the Arabic word *al-sāqiyah* (سقي), meaning “irrigation channel.” In the Americas, the development of acequias by the Spanish newcomers benefited from the sophisticated autochthonous irrigation culture developed by the indigenous peoples and their environmental wisdom. This knowledge reached back to Europe, Africa, and Asia in the form of an astounding repertoire of agricultural species previously unknown in the Old World.

Acequias are technological systems that are designed, maintained, and operated to meet a variety of productive goals, social services, and health needs, with the practice of irrigated agriculture being of paramount importance. In preindustrial times, acequia systems relied on the force of gravity for the collection, conduction, distribution, recollection, and discharge of each system’s waters—with the only exception of systems fed by water captured from streams or the water table by means of implements operated by animal or human force.

Another defining trait of the preindustrial acequia systems was the fragility of the channel network in terms of its physical fabric. In olden times, acequia ditches were mere trenches open in the fields. Strong, long-lasting stone or masonry constructions were limited to critical points in the network, such as the acequia water intake or the water dividers. As a result, the intangible dimension of acequia systems was stronger than the tangible one. The intangible component of acequia systems was composed of the design

and operational knowledge, the organization of the community of users, and the customary laws and practices governing the system’s operation.

The design of acequia systems required a deep understanding of local environmental and geographic conditions to fulfill the goals of the community with the locally available resources. Water had to be collected and conducted to the leveled fields by means of the carefully leveled main canal and distribution branches. Too much slope would erode the channel network and the agricultural lands, while too little slope would hinder the water circulation and allocation process, with the risk of compromising the fertile lands because of water stagnation. Particular species of trees were planted or allowed to grow along the main channels to reinforce them. Irrigated fields were furrowed with shapes and dimensions related to water availability and the water requirements of the crops cultivated. A selection of vegetal agricultural species had to be made according to the quality and quantity of irrigation water available as well as the insolation, rainfall, and wind regimes.

The different water uses served by the acequia flow were rationally inserted into the system according to careful evaluation and clear-cut principles. Points for human and animal water consumption were placed first, followed by uses that did not consume or pollute waters, like grist milling, which needed adequate flows, and then diversion for irrigation (which reduced flows and made operating water mills difficult). Water-polluting handicraft industries and community health facilities (such as baths, laundries, and sewage) were usually placed at the end of the secondary distribution channels.

Yearly communal maintenance of the irrigation works was crucial to avoid decreased performance or even the collapse of acequia systems by silt deposits, excessive vegetation growth, or the crumbling of the earthen channels. Community works were supervised by community-elected acequia officers who ensured the compliance of acequia customary uses, rules, and regulations. Each of these aspects governed the user’s contribution to common maintenance and their access to water while preventing and punishing anti-systemic behavior.

No matter their scale, all acequias are complex, smart systems whose value for contemporary humanity has beautifully arisen from their foundational weaknesses. Forced adaptation to local conditions has produced an extraordinary variety of acequia waterscapes, from the desert oases to the mountain terraces, that today encourage agrobiodiversity. Negotiations among users have resulted in systems designed to reduce the potential for water conflict and withstand the recurrent crises caused by droughts and floods.

Dependence on communal work and self-organization has strengthened local communities and promoted the development of rituals that, along with the particularities of their own acequia landscape, have sustained local identity.

In addition, water seepage inherent to earthen ditches and flood irrigation recharges aquifers, washes salts and pollutants from fertile soils, and enhances biodiversity. Even evapotranspiration results in positive services to the community, such as reducing the urban heat island effect and helping rain to fall on the river headwaters, as research pioneered by Millán Millán has proven in the Valencia region of Spain.

Acequias are old. Very old. Throughout the centuries, acequias have overcome periodic environmental crises, rivalries among water users, and profound historical changes. And they have survived because of their common-good oriented design that is based on principles, such as cooperation, water sharing, respect, equity, transparency, fairness, mediation, negotiation, proportionality between water allocation rights and systemic maintenance duties, and solidarity. Their maintenance, which has supported agriculture, stockbreeding, and other valuable productive activities, has always been beneficial for the acequia users (men as well as women—whose role in the development and upkeep of acequias has been downplayed) and local communities.

Acequias have thus passed the test of sustainability. In the face of the challenges posed by hyper-industrialization, globalization, and climate change, acequias encapsulate a wealth of lessons in strategic issues, such as food quality, food security, and water and soils preservation. Significantly, the United Nations is promoting the global implications of what José A. Rivera appropriately called “the acequia culture.” UNESCO fosters the preservation of traditional irrigation systems and landscapes under the 1972 Convention Concerning the Protection of the World Cultural and Natural Heritage and the 2003 Convention for the Safeguarding of the Intangible Cultural Heritage. And the Food and Agriculture Organization of the United Nations is implementing a program for the safeguarding of Globally Important Agricultural Heritage Systems, which has already recognized acequia and acequia-like irrigation agroecosystems throughout the world.

Because of their awareness of the multiple values of their treasured acequias and their commitment to the research, dissemination, and preservation of knowledge, especially in cooperation with committed scholars such as the ones that made this book possible, the New Mexican traditional irrigators—the *parciantes*—are a leading example among traditional irrigators worldwide.

In countries like Spain, the extensive concrete lining of acequias long ago caused the loss of rituals inherent to performing communal maintenance. The multi-secular urbanite contempt toward the farming lifestyle (as well as the lack of a holistic approach to the understanding of entities like the Water Tribunal of Valencia) has helped to obscure the acequia system values. The direct discharge of urban and industrial wastewaters into the acequia networks has not helped to promote the appreciation of acequias by the public throughout the 20th century. Nowadays, the impact of urban and public infrastructure development and the substitution of acequias by computerized fertigation systems under the false premise that flood irrigation “wastes” water, combined with the dramatic decrease and aging of full-time acequia farmers, are all threatening the very survival of acequias.

Acequia safeguarding requires scientific identification and social dissemination of the values and services provided by acequias. Global acequia action has to become a moral imperative if we want these superb tangible and intangible, cultural, and natural systems to survive and to inform policies that are aimed at countering climate change and ensuring the sustainable livelihood of local communities.

The meaningful outcome of the multidisciplinary study of New Mexican acequias as presented in this volume will be a precious source of inspiration for acequia irrigators and supporters worldwide.

**Luis Pablo Martínez Sanmartín**  
Historian and Anthropologist  
València, Spain, September 26, 2020



## EDITOR'S PREFACE

**I**n 2010 under the leadership of Principal Investigator Sam Fernald, the research project, *Acequia Water Systems Linking Culture and Nature: Integrated Analysis of Community Resilience to Climate and Land Use Changes*, was awarded a \$1.4 million grant by the National Science Foundation (NSF). NSF's specific grant program, Dynamics of Coupled Natural and Human Systems (CNH), "supports interdisciplinary research that examines human and natural system processes and the complex interactions among human and natural systems at diverse scales." The goals of the *Acequia Water Systems Linking Culture and Nature* project were to understand the links between culture and nature in the context of *acequias*. The central hypothesis was that *acequias* create and maintain the relationships between humans and nature that will allow for resilience in the face of climate change and increasing population growth. In addition, community members, mainly those from underrepresented groups in rural Hispanic minority communities, were integrated into the research itself. Overall, the study provided entirely new insights into relationships between water management systems, communities, and landscapes.

From an ambitious list of project deliverables, this book, *Acequias of the Southwestern United States: Elements of Resilience in a Coupled Natural and Human System*, was conceived in order to document the researchers' various findings and to bridge the chasm between the academic analysis of a subject(s) and its translation for the public. In the spirit of the commons, it strives to provide useful information and access for all persons, not only those studying the ditch system from a bustling university library or pecking the keys from a staffer's laptop in our state's capitol but also those whose minds and hands and fortitude actually compose and give life to the *acequia*—the *parciantes*, *mayordomos*, *comisionados*, and the larger *acequia* community.

The coauthors, 16 in total, are some of the brightest and most ambitious that New Mexico's institutions have cultivated. They largely represent New Mexico State University, the University of New Mexico, and Sandia National Laboratories, and draw from the fields of hydrology, anthropology, ecology, agronomy, regional studies, animal and range sciences, natural resource management, and agricultural economics. Moreover, two of the coauthors, Dr. José Rivera and Dr. Sylvia Rodríguez, grew up in the *acequia* communities of Mora and Taos, respectively, and have contributed several well-known academic works to a growing body of knowledge that Dr. Rivera

poignantly refers to as "*acequia studies*." Dr. Rodríguez and Dr. Rivera's experiences give readers and fellow researchers a perspective that only those whose ancestors have lived and worked by the *acequias* can possess. The culmination of the several coauthors' respected knowledge and experiences makes this truly a well-rounded, interdisciplinary, and interinstitutional work, an ecosystem of ideas and talents unto itself.

*Acequias of the Southwestern United States* has been an extraordinary opportunity for me professionally. Aside from the personal intellectual fulfillment this project has granted me, I was stimulated by the complex undertaking of editing eight, very unique pieces—each written by distinguished, deep thinkers—and assembling a cohesive document that can be read as one seamless text or as several independent chapters. Furthermore, I was tasked with making the book accessible both to the wider public and specifically the audiences of New Mexico. The coauthors and editing team worked together to form, reform, and polish each chapter in order to add, what we consider, a unique and significant interdisciplinary contribution to New Mexico's *acequias*, agriculture, *acequia cultura*, and the body of "*acequia studies*" literature.

I want to thank the following contributors. First my boss, Dr. Steve Guldán, for his constant encouragement and availability to sit and discuss the book and all its intricacies. Dr. Sam Fernald for his work as head PI and his editing assistance. Sam has put in an incredible amount of time leading this group and making sure the grant was a success not only for the research team but also for the *acequias* themselves. Dr. José Rivera for his editing "eagle eyes" and engaging conversations. The coauthors and their immense commitment and time working with me as we plucked through several drafts of each chapter. Ana Henke and Frank Sholedice as they worked with me on small and large editing questions that arose as well as the final editing and layout process. Finally, a large thank you to the people who hold the knowledge of the *acequias* in their hearts and in their hands, from those who came before to those who will come after.

**Adrienne Rosenberg**

Editor, NMSU Sustainable  
Agriculture Science Center, Alcalde  
October 29, 2020

# Key Concepts for a Multidisciplinary Approach to Acequias

Sylvia Rodríguez

---

New Mexico's *acequias* belong to a family of hand-dug, gravity-flow, small-scale, farmer-managed irrigation systems found all over the world. Despite their differences in terms of environment, geography, climate, regional and national setting, language, and culture, these systems all operate in strikingly similar ways. This has led one anthropologist to propose that their common operating principles are the result of a rare process of convergent evolution, whereby the same form emerges independently in different places and times because it is highly adaptive (Trawick et al., 2014). Such systems, which are found, for example, in the Andes, Mexico, Spain, Switzerland, China, India, Nepal, the Philippines, Africa, and Bali, have proven to be sustainable and resilient within their respective ecological settings, whether arid or humid. Nevertheless, many have disappeared under the onslaught of modernization, while those that still exist struggle to survive in the face of myriad adverse political, economic, social, demographic, environmental, and climatic forces.

Why should non-farmers, city dwellers, scholars, scientists, policy makers, planners, or politicians care about acequias or other small-scale, self-organized irrigation systems? Those who belong to or who study such systems are convinced of their value because these systems have worked for a long time, and acequias therefore offer lessons about how to manage water. But, you may ask, even if such systems worked so well in the rural past, isn't their gradual disappearance an indication they can no longer function in today's modern, urban world? Besides, do the operating principles that served so well at small to medium scales apply to the ever more complex scales of modern cities, nation states, and continental transborder settings?

The looming specter of anthropogenic global climate change raises serious questions about just how ecologically adaptive modern industrial and postindustrial technology is proving to be in the long run. The emerging crisis has begun to shift research agendas across disciplines as regions and nations are faced with the grim prospects climate scientists foresee for the 21st century. Hence the growing number of research programs dealing with questions of sustainability, resilience, systems modeling, and the investigation of **coupled natural-human systems**. On the one hand, our dilemma calls for new paradigms and innovative technologies. On the other, traditional preindustrial technologies

lately considered backward and obsolete now bear another look for what they might teach us about sustainable, resilient adaptive strategies. Ancient and extinct systems also offer insights about the trajectories and conditions involved in long-term social, technological, and environmental change. In short, given the gravity of our situation, scientists, humanists, policy makers, political leaders, and regular citizens need to reconsider and modify the ways we inhabit, think about, and interact with our local as well as regional, national, and global environments.

This brings us back to acequias and to the principal study giving rise to this volume, which comes out of a five-year, approximately \$1.4 million research project funded by the National Science Foundation (NSF) designed to investigate acequias and their watersheds in terms of **dynamically coupled natural and human systems** (CNH). As McConnell et al. (2011) wrote in their report on Coupled Human and Natural Systems (CHANS), also known as CNH,

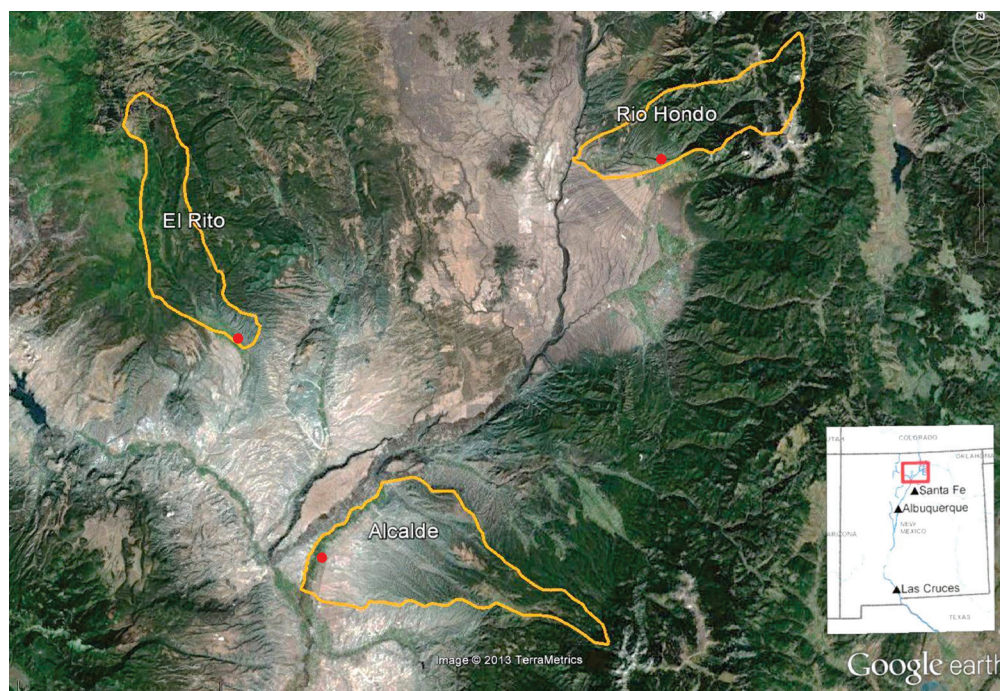
The CHANS approach builds on a long tradition of scholarship on human-nature interactions, and CHANS scholars may equally find themselves at home in research communities addressing human-environment systems, social-ecological systems, ecological-economic systems, or population-environment systems. What distinguishes the CHANS approach is an explicit acknowledgement that human and natural systems are coupled via reciprocal interactions, understood as flows (e.g., of material, energy, and information). Of particular interest in studying these interactions is the understanding of feedbacks, surprises, nonlinearities, thresholds, time lags, legacy effects, path dependence and emergence (Liu et al. 2007a) across multiple spatial, temporal and organizational scales. Strategically, the CHANS approach seeks understanding of such complexity through the integration of knowledge of constituent subsystems and their interactions. Operationally, this involves linking submodels to create coupled models capable of representing human (e.g., economic, social) and natural (e.g., hydrologic, atmospheric, biological) subsystems and, most importantly, the interactions among them.

The project investigated acequia systems at three study sites located in different watersheds in Northern New Mexico: El Rito, a tributary of the Rio Chama; Alcalde, located on the main stem of the Rio Grande; and the Rio Hondo north of Taos, a tributary of the Rio Grande (Figure 1). It was conducted by researchers in several disciplines at three universities (New Mexico State University, the University of New Mexico, and the New Mexico Institute of Mining and Technology) and a national laboratory (Sandia National Labs), working in cooperation with the New Mexico Acequia Association and local farmer-irrigators or *parciantes*.

The goals of the CNH Acequia Project (originally titled “Acequia Water Systems Linking Culture and Nature: Integrated Analysis of Community Resilience to Climate and Land Use Changes”) were to “understand acequia-moderated linkages between culture and nature and to quantify community survival tipping points” (Fernald et al., 2009). Its objective was to “quantify the role of acequias in hydrologic buffering, community resilience, and ecosystem health” (Fernald et al., 2009). The project was designed to test the hypothesis that “traditional acequias create and sustain intrinsic linkages between human and natural systems that increase community and ecosystem resilience to climatic and socioeconomic stresses” (Fernald et al., 2009). The project came under an NSF initiative to promote investigation of coupled natural and human systems.

The core research team consisted of 10 individuals who worked together on this project for a period of five years. It included four hydrologists (one a systems modeling specialist), an agricultural economist, an agronomist, a rangeland ecosystems specialist, a wildlife biologist, a professor of community planning and noted acequia scholar, and myself, an anthropologist who studies and works with acequias.<sup>1</sup> A number of graduate students earned their degrees working on the project. The chapters in this volume will present the group’s cumulative findings.

This chapter gives my overview as an anthropologist who joined the project as a consultant rather than principal investigator. I participated in the regular ongoing processes of discussion and monthly conference calls, analysis, theorizing, planning, reporting, critique, semi-annual retreats,



**Figure 1. Map of the three research sites and watersheds.**

and composition of multi-authored papers. In addition, I was tasked with organizing an international symposium and workshop on acequias and other community irrigation systems in a comparative global perspective. I also guest curated an exhibit on acequias for the Maxwell Museum of Anthropology at the University of New Mexico (UNM). The following section will describe the **moral economy model**, which is fundamental to my understanding of how acequias and other autonomous irrigation systems operate. Then I will discuss how the process of multidisciplinary collaboration brought distinct conceptual and methodological interfaces into relief and advanced our thinking about water and society as unitary and inseparable rather than coupled (dual and therefore implicitly separate) systems. A brief section will deal next with the international symposium/workshop and museum exhibit. The final section will conclude with ideas and issues regarding future research.

## **MORAL ECONOMY**

The moral economy model of community irrigation management posits a system of principles and values that supports and guides cooperative, independent economic practice. Anthropologist Paul Trawick (2003) defined the moral economy of water as:

A concrete ethic based on a well-defined set of practices, rules, and norms, and corresponding material relations. These have to do with the proper use of vital resources—land, water, and labor—and the ways that individuals should relate to each another, through



the central reality of work, and to the community as a whole. Although the moral economy is inward-looking, focused on internal social interaction, it is also a 'political' economy, as any such ethical system must be by definition, and of course it does not exist in isolation.

Drawing on the work of Elinor Ostrom and his own ethnographic research in highland Peru and Valencia, Spain, Trawick identified nine operating principles common to all small-scale, farmer-operated irrigation systems: autonomy, alternation or turn-taking, contiguity in distribution, uniformity, proportionality, transparency, boundary maintenance, direct feedback, and graduated sanctions (Trawick et al., 2014).<sup>2</sup>

Like their Iberian-Islamic forebears and modern cognate in Valencia, acequia irrigation systems clearly exhibit all of these attributes. Acequias operate as autonomous common property regimes while at the same time they are legal subdivisions of the state, subject to state statute. An **acequia association** consists of farmer-rancher *parciantes* and landowners who share a common stream diversion (*presa*) into a hand-dug *acequia madre* ("mother ditch") from which laterals (*linderos*, *sangrias*, or *venitas*) channel water to individual properties. *Parciantes* are obligated to pay dues, contribute labor to the cleaning and maintenance of acequia infrastructure, observe the customary principles of water sharing, and annually elect a *mayordomo* or ditch boss and three commissioners who oversee ditch management and governance. Labor contribution and water allocation are proportional to the amount of acreage a *parciante* irrigates. The *mayordomo* allocates water proportionally to *parciantes* in good standing on the basis of equity and need, supervises communal labor on the ditch, and resolves disputes over water. Commissioners usually include a secretary, treasurer, and president, who in concert with the *mayordomo* oversee all ditch business. Acequia communities are by definition place-based, territorial, and linked through time by kinship, spatial contiguity, and a continuous round of sacred and secular calendric and lifecycle rituals.

Moral economy finds expression in norms, values, sensibility, ethos, and worldview. The principle of *ayuda mutua*, *mutualismo*, or *mutualism* is central to acequia moral economy and pervasive in other local organizations, including *Penitente* or other lay religious *cofradías* (confraternities or brotherhoods), mutual domestic water associations, land grant associations, burials, and other mutual aid associations. Mutualism involves an enduring bond of reciprocal economic aid and interdependence among participants. José Rivera devotes a chapter ("The Roots of Community in the Northern Rio Grande: Acequia Mutualism, Cultural Endurance, and Resilience") to mutualism and acequias in this volume. *Confianza* (trust) and *respeto* (respect) are key elements of acequia moral economy. *Confianza* is the reciprocal trust shared between kin, friends (*compadres*), and *vecinos* (neighbors) with whom one can

speak in confidence and rely on in times of need. *Respeto* prescribes how to treat others across the spectrum of age, gender, and class—in order receive or earn respect in turn. Those individuals who enjoy respect or what social scientists call **social capital** voluntarily devote time, energy, and resources to the common good (the acequia, mutual domestic water association, parish, *morada* or Penitente chapter-house, school), ideally without ever calling attention to it. Anthropologist-sociologist Pierre Bourdieu (1984) defined social capital as "a capital of connections, honourability and respectability" related to but distinguishable from economic and political capital. In their groundbreaking work on collective action problems, Ostrom and Ahn (2007) clarified the concept:

We have elected three types of social capital that are particularly important in the study of collective action: (1) trustworthiness, (2) networks, and (3) formal and informal rules and institutions. We view social capital as an attribute of individuals and of their relationships that enhance their ability to solve collective action problems.

Every acequia comes down to the commitment and ongoing interaction of a critical number of *parciantes* who irrigate, pay their dues, contribute labor, come to meetings, vote for officers, respect the *mayordomo*, observe local water sharing custom, negotiate ditch matters, and themselves serve as *mayordomos* or commissioners. Whereas a century or more ago the acequia moral economy of water was tied directly to the subsistence economy as well as material and physical survival, today it underpins the maintenance and defense of a land base with associated water rights and a distinct sociocultural identity.

Acequia self-awareness and activism have emerged in response to the multiple, intensifying pressures that threaten the survival of acequia communities: changing land use patterns accompanied and/or driven by demographic, economic, social, cultural, and environmental changes. Starting in the late 1970s, acequia associations began forming coalitions to defend themselves against threats posed by water rights transfers away from agricultural use; real estate, tourism, and urban development; surface water pollution; and large-scale hydraulic projects triggered by federal and state water right adjudication lawsuits that opposed senior to junior water rights claims.<sup>3</sup> Scholarly, scientific, and popular interest in acequias has been stimulated by and grown concurrently with the emergence of acequia activism.

## COLLABORATION

Like water management, acequia research requires collaboration. Research on acequias must be collaborative or multidisciplinary because no single discipline or methodology can encompass and adequately account for how acequias operate as integral components of hydrological, biological, ecological, economic, political, and social systems.

Successful research on acequias also depends on cooperation—if not collaboration—with *parciantes* themselves. The CNH Acequia Project (CNHAP) secured the cooperation of *parciantes* and commissioners in each of the study sites, but these individuals did not collaborate in the design or execution of the research. However, the New Mexico Acequia Association did help to design and participate in focus groups carried out with *parciantes* and also provided critical input for the survey. While I have worked collaboratively with acequia associations for many years, the CNHAP was my first collaboration with a multidisciplinary team of scientists engaged in the collection of quantitative data. My own research is ethnographic and qualitative, with a current focus on the micropolitics of interpersonal relations that keep an acequia going in the face of escalating challenges to its survival. Of particular interest to me is how social standing and personal agency interact on a daily basis through time on a particular ditch in a particular community.<sup>4</sup> This intimate scale of ethnographic observation differs from and yet complements the **system dynamics modeling** approach that calibrates variables likely to tip the balance toward acequia extinction (for a detailed discussion of the model, see “Connection and Integration: A Systems Approach to Exploring Acequia Community Resiliency” in this volume).

From the outset of the project, our team pursued lively conversation about how to translate different conceptual and methodological languages into a common framework that ideally could be made comprehensible to a non-academic audience. A conceptual model was first developed using **causal loop diagrams**, which help one visualize the relationship of different variables in a system. Mutualism was a key variable in the causal loop diagrams generated by the system dynamics modeling process.

... our DH [dynamic hypothesis] was focused on the relationship between community structure and resource management in traditional acequia communities of [N]orthern New Mexico. Acequia communities were built on CPR [common pool regime] practices, such as sharing uplands resources (e.g., grazing) and water for agricultural production in the floodplains, collective-knowledge transmission to descendants, embedded community mutualism, and cooperation of community members. Mutualism, in this context, can be described as the shared, communal responsibility of local residents to maintaining traditional irrigation policies and upholding cultural and spiritual observances unique to their family and acequia’s lineage... (Turner et al., 2016).

Still, no attempt was made to operationalize and measure mutualism as such. It would border on anathema and disrupt rapport to attempt to enumerate and assign values to the time, resources, love, and labor people voluntarily devote to kinship and neighbor-based reciprocity in the

form of ritual, acequia, and other community activities. Yet mutualist behavior is easily observed. The study nevertheless aimed to integrate qualitative and quantitative variables into a unified system dynamics model. A main objective of system dynamics modeling is to gauge potential tipping points in order to predict, forestall, avert, adapt to, or plan for significant gradual or sudden change:

A key contribution of this model was the incorporation of a number of socio-economic and cultural variables... whose dynamics of interest are fairly well understood historically but where little to no quantitative data exists to inform the model (e.g., how irrigators manage their time or how demographics effect [sic] mutualism)... This remains problematic for acequia modeling research since much of the desired data resides in the human dimensions of the acequia system and determining how to quantify results into a working model remains challenging. For these reasons, we took a systems modeling approach and tested the sensitivity of uncertain parameters for which better quantitative description is unlikely... but which equally fit the observed historical data that was available. Not only was the variability regarding these parameters quantified but several socio-cultural leverage points were identified through the process (e.g., enhancing community participation). The knowledge gained regarding the variability of model behaviors will be carried forward to interpret acequia community response to disruptive events and adoption of adaptive strategies. However, the creative capacity of acequia communities and leaders likely exceeds the knowledge embedded within the historical record. For this reason, modeling of community adaptations must be done in tandem with acequia stakeholders, who in real-time have the capacity to anticipate upcoming challenges and create and manage novel strategies to address those challenges (Turner et al., 2016).

## CONNECTIVITY

Another key concept for the CNHAP was connectivity. **Connectivity** refers to dynamic linkages that operate across a range of physical and social phenomena and scales that are amenable to quantitative and/or qualitative approaches. The study evolved in part out of earlier research into hydrological connectivity between surface water and groundwater that demonstrated how flood irrigation recharges the shallow aquifer and stream system, a phenomenon and important **ecosystem service** long familiar to *parciantes* in the upper Rio Grande valley (Fernald and Guldan, 2006). The CNH project also investigated connectivity between upland and lowland watershed zones, hydrologically as well as in terms of complementary agropastoral land use patterns (see the following chapters in this volume: “Surface Water and Groundwater Interactions in Acequia Systems of Northern New Mexico,” “The Role of Livestock in Supporting Ace-

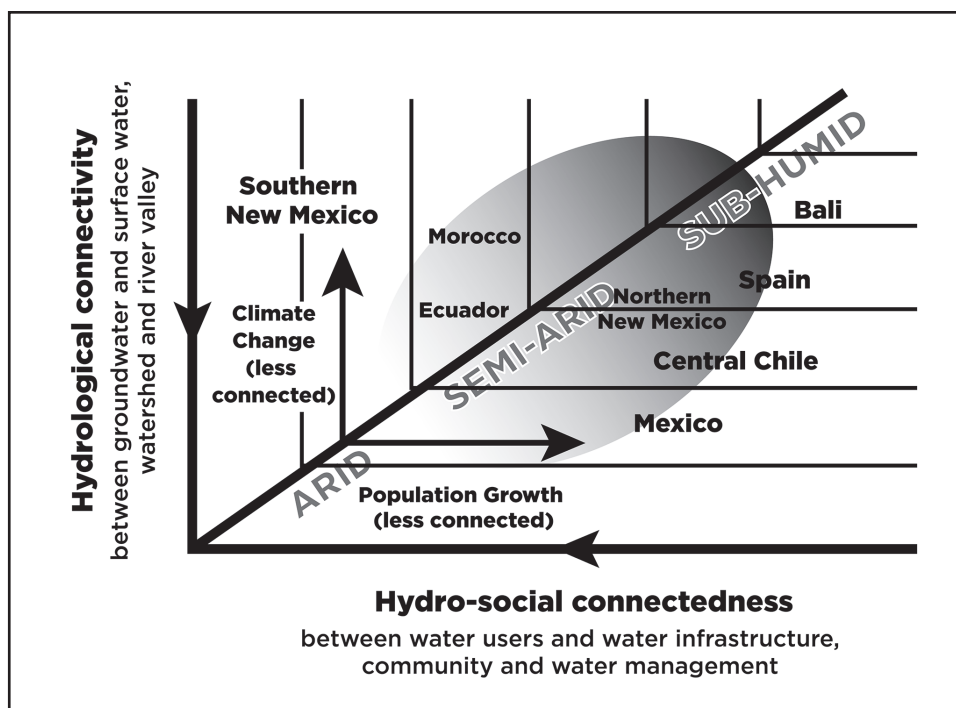


quia Communities of Northern New Mexico,” “Acequia Ecosystems,” and “Perceptions of Drought Preparedness and Adaptation Strategies within Acequia Communities”). Connectivity is embodied in the network of ditches that comprises an acequia system, linking it to other systems on the same or neighboring streams. The contiguity between irrigated properties on acequias along a stream is a related manifestation of connectivity, as is the social fabric of kinship and of mutualism.

External connectivity at larger socioeconomic scales can negatively affect the internal viability of an acequia system, for example through urban development and by drawing parcientes away from agriculture into other kinds of wage or salaried work and urban centers and lifestyles. This has caused increasing attrition in acequia participation since at least World War II and threatens acequia survival. In their research on the Taos Valley acequias, for example, Cox and Ross (2011) concluded that

... acequias that have been exposed to these disturbances [of land right fragmentation and urbanization] are producing fewer crops per unit area than other acequias in the valley. In many areas around the world, the increasing economic connectivity that these disturbances represent is impinging on the historical practices of community-based management regimes that employ common property arrangements. Such connectivity may afford new opportunities, but we should not be surprised if it can come at a cost. In this case, the cost... has involved decreased interdependence and solidarity both within and between acequias, as they are less involved in historic traditions and rituals, and more involved in the larger and more developed economy through wage-earning jobs and local markets.

One of the papers the CNHAP team produced for a conference on irrigation held in Valencia, Spain, explored the relation between hydrologic and social connectivity in coupled (hydrologic and human) systems as the basis of resilience in acequia communities (Fernald et al., 2014). This ambitious paper sought to formulate a hypothetical correlation between hydrologic and social connectivity without



**Figure 2.** Conceptual diagram of the relationship between resilience and hydrologic connectivity and hydro-social connectedness (Fernald et al., 2014).

reducing either to the terms of the other. It also sought to place this formulation in a comparative context, drawing on case materials presented by participating scholars at the international symposium sponsored by the CNHAP the previous year (see below and in the Appendix). The conceptual bridge for this blending of natural and social scientific perspectives turned out to be **hydro-social cycle theory**, enabled by the open-minded acknowledgment on the part of the hydrologists that water is social. A long excerpt and conceptual diagram from the paper are presented below in order to show how we came to our conclusions.

Based on our research and papers presented at a global acequia symposium held in New Mexico in 2013, resilience of community irrigation systems appears to be closely related to hydrologic connectivity and hydro-social connectedness. We have started to put these relationships together in a conceptual diagram (Figure [2]). The figure shows hydrologic connectivity in terms of watershed connections to river valleys and groundwater connection to surface water. Climate change with increased temperatures and reduced water supply may lead to reduced hydrologic connectivity. The figure also depicts hydro-social connectedness in terms of the community irrigator interactions with water delivery infrastructure and community member participation in water management organization. Population growth and urbanization are example drivers that lead to land use and economic changes that reduce hydro-social connectedness.

A confluence of conditions appears to exist in semi-arid systems that is particularly resilient, as depicted by the gray shaded space in Figure [2]. Northern New Mexico has a dry enough climate to require community involvement in water management but has enough water to maintain hydrologic connectivity, and the systems are resilient. Two sites are losing resilience: in southern New Mexico, arid climate and reduced water availability from drought have led to disconnected surface water and groundwater that reduce sustainability; in Bali, water temples tied to religion and irrigation have been seriously impacted by changing society and government policies. Sites with borderline resilience include: Spain impacted by urbanization; Mexico impacted by government centralization and reduced user involvement; Central Chile where government policies have disbanded ditch management cooperatives; Ecuador where climate change has reduced snowpack; and Morocco where water delivery infrastructure modernization has led to a disconnected community (Fernald et al., 2014).

The Figure 2 diagram postulates a pattern of correlation that calls for refinement through closer examination and comparison of the regional case materials.

## THE HYDRO-SOCIAL CYCLE

The CNH framework seems to edge toward paradox in that it strives to explain the dynamic, living interaction at multiple scales between two domains considered fundamentally separate and distinct: nature and culture. The conceptual division between natural and human or social domains is foundational to modern science and underpins its technological mastery over the physical world. In his brilliant critique of what he calls “modern water,” Linton (2010) observed that

As the dominant epistemological mode of Western culture, scientific practice has produced a distinctive way of understanding and representing water that makes it appear timeless, natural, and unaffected by the contingencies of human history.

Modern water is an abstraction represented by the chemical formula  $H_2O$  and the hydrological cycle famously diagrammed by Robert Horton in 1931. It is described and explained as an objective phenomenon, external to human society. Its processual or cyclical transformation into liquid, vapor, or ice is seen as universal and everywhere the same (Linton, 2010). Instead, proponents of the hydro-social cycle approach counter that water and its social context are historically co-constituted as a socio-natural process. As Linton and Budds (2014) put it,

Our approach diverges from many existing approaches to water-society relations and water politics by calling

the very nature of water into question. We start from the premise that water internalizes social relations and politics, as opposed to being merely the object of politics. Through the hydrosocial cycle we seek to transcend the dualistic categories of ‘water’ and ‘society’, and employ a relational-dialectical approach to demonstrate how instances of water become produced and how produced water reconfigures social relations. We argue that unravelling this historical and geographical process of making and remaking offers analytical insights into the social construction and production of water, the ways by which it is made known, and the power relations that are embedded in hydrosocial change.

In this perspective, water, irrigation, and acequias are more process than thing, even though we habitually refer to them as things. Moreover, they have agency. In 2014, the CNHAP team started adopting the term “hydro-social” to describe the kinds of hydrological and social connectivity they were trying to capture in the system dynamics model. The hydro-social cycle concept makes good anthropological sense, but its practical implications for quantitative methodologies need to be worked out. In CNH terms, acequia systems mediate, or constitute a hydrological and social buffering mechanism, between human and natural domains. In hydro-social cycle terms, acequia systems are ecologically, historically, and politically situated socio-natural hybrids.

## SYMPOSIUM, WORKSHOP, AND EXHIBIT

The public and international face of the CNHAP took the form of a well-attended symposium and a widely visited museum exhibit. The symposium (“Acequias and the Future of Resilience in Global Perspective”), held in March 2013, brought together scholars known for their research on autonomous irrigation systems in various parts of the world with acequia researchers, activists, and community members. Held for two days in Las Cruces, New Mexico, it was free and open to the public. It featured two panels made up of CNHAP team members who reported on their findings, and two panels made up of invited scholars who spoke about their research in Spain, the U.S., Chile, Bali, Peru, Mexico, Morocco, and the Mediterranean. The panels were followed on the second day by an open workshop in which acequia researchers and activists shared ideas and prospects for future research. The symposium program and abstracts are found in the Appendix, and audio recordings of panel sessions and the workshop can be found at the following Cultural Energy link:<sup>5</sup> <http://www.culturalenergy.org/acequia.htm#AcequiasGlobal>

The exhibit about acequias (“El Agua es Vida: Acequias in New Mexico”) was on display in the main gallery of the UNM Maxwell Museum of Anthropology between May 2014 and June 2015 (<https://maxwellmuseum.unm.edu/exhibits/temporary/el-agua-es-vida-acequias-northern-new->

mexico). The exhibit deployed curated artifacts, objects, photographs, video, and text to depict acequias historically, hydrologically, and in terms of a heuristic framework of watershed/water regime/waterscape.<sup>6</sup> Approximately 25,000 people saw the exhibit. Before it was dismantled, a video record was made of the exhibit at the UNM Arts Lab in order to produce a virtual online version presumably forthcoming.

## WHERE DO WE GO FROM HERE?

There is a lot we do not know about acequias empirically. The New Mexico Acequia Association has documented 547 acequia associations in the state and estimates a total of around 700. Another 75 are said to operate in the San Luis Valley of southern Colorado. Fragments of information about the number, physical condition, history, membership, operation, agricultural productivity, challenges, and needs of acequia systems are scattered across a range of agencies, organizations, institutions, and researchers, but no central archive pulls all the data together. Given the autonomous, often fiercely independent and defensive character of acequia associations, the desirability of a centralized data source and questions of who would control and have access to it are not foregone conclusions.

Today, more than ever before, acequias attract the curiosity and interest of scientists, scholars, journalists, students, photographers, artists, writers, tourists, and others. Every month I receive inquiries from individuals who want to study, write about, or photograph acequias and acequia activities. The annual spring cleaning or *limpia* is a photographic favorite. An issue that should concern anyone with a serious interest in acequias is ethical responsibility and accountability not only to one's discipline or employer but to those one presumes to study. Only rarely do acequia associations or *parciantes* get access to or benefit from the material that others collect about them. Researchers invariably promise to send copies of their studies, papers, photographs, or articles to their subjects, but rarely do so. For better or worse, acequia associations cannot exercise the sovereign status that enables Native American tribes to control access by prospective researchers, determine what kind of research is permitted, or constrain the dissemination of findings.

Yet, as said earlier, genuine research on acequias depends on a minimal degree of local cooperation if not collaboration. Cooperation and collaboration reside along a continuum, with polite cooperation (informed consent and assent with asymmetrical scientific/investigative control) at one pole and participatory action research at the other. The first is conventional scientific practice in which the research question, design, and control of data belong to the researchers, usually academics. This is standard extractive research. The second is research generated, designed, and controlled by a community of interest (made up of community members, activists, and scholars) seeking to understand and

respond to a specific problem or set of conditions they are concerned about. Most current anthropological and other field research on acequias is located somewhere along the middle of the continuum, including the CNHAP. My recommendation is that research on acequias be carried out between the midpoint and participatory end of the continuum. The questions most worthy of investigation would be those that equally serve acequia and scientific/scholarly interests.

## ENDNOTES

1. Other collaborators on the project included José Luis Arumí, Professor (Civil Engineering) at the Universidad de Concepción, Chile; and Quita (Marquita) Ortiz of the New Mexico Acequia Association, who participated in conference calls and retreats through 2014 and was listed as a coauthor on several papers.
2. Trawick et al. (2014) elaborated on these widespread operating principles as follows, specifically with reference to Valencia, Spain. He has also documented these principles for highland Peru, and they characterize New Mexican acequias as well.

*Autonomy:* Each community has and controls its own flow of surface water, which is distributed and used according to customary rules.

*Alternation or turn-taking:* The sets of communities on either side of the river cooperate by alternating in extracting their assigned flows in such a way that they irrigate together in a single cycle; their individual farmers do likewise, taking turns in order to share the resource in the same coordinated way.

*Contiguity in distribution:* Within the communities in each half of the system (i.e., on the two sides of the river), water is distributed to fields in a relatively fixed contiguous order based only on their location, starting at the upper end and moving systematically downward, canal by canal and field by field, until all of the eligible lands have been irrigated.

*Uniformity (one component of equity or fairness) among rights:* All entitled fields receive water with the same frequency so that the impact of the prevailing scarcity is shared and absorbed evenly by all of them.

*Uniformity in techniques:* All farmers irrigate their crops in the same way, using one of two standard methods that in each case impose an upper limit on water consumption and on irrigation time, thereby creating a fairly uniform land-to-water ratio throughout the canal system.

*Proportionality* (the other component of equity) *among rights*: In taking their allocated turns, irrigators use only the amount of water to which the extent of their land, and the specific watering technique being utilized, entitle them.

*Proportionality among duties*: People's contributions to canal maintenance must be proportional to the amount of irrigated land that they have, and thus to the amount of water that they use (also between rights and duties).

*Transparency*: Everyone knows the distribution rules and, because the proper order of turns is fixed and contiguous along each canal, they have the ability to confirm, with their own eyes, whether or not those rules are being obeyed in order to detect and denounce any violations that occur.

*Boundary maintenance*: Any unauthorized expansion of irrigation, which would lower the frequency of water use for everyone, is prohibited.

*Direct feedback on the level of free riding*: The frequency of water use for everyone is determined, in a direct and obvious way to each farmer, by the extent to which people are obeying the rules.

*Graduated sanctions*: The penalties for rule violations are severe but vary according to the gravity of the offence.

3. This includes the Pueblo water right adjudication cases known as Aamodt (involving the Pueblos of Nambé, Pojoaque, Tesuque, and San Ildefonso; the State of New Mexico; the United States of America; the City of Santa Fe; Santa Fe County; and representatives of non-Pueblo water users) to settle the Pueblos' water right claims in the Pojoaque Basin; and Abeyta (involving the Pueblo of Taos, the Taos Valley Acequia Association [representing 55 acequias in the Taos Valley], the Town of Taos, Mutual Domestic Water Associations, the El Prado Water and Sanitation District, the State of New Mexico, and the United States of America.) These decades-long cases were triggered by the importation of Colorado River water into New Mexico via the San Juan-Chama Diversion Project and sought to settle Pueblo water claims and all junior claims on the Rio Grande and Rio Hondo (Taos), starting with the acequias.
4. Personal agency refers here to the capacity of an individual to influence others' actions, attitudes, and decisions, and thereby affect the mood or course of events within a local community. This capacity may be neither authoritarian nor coercive but based instead on personal and to some degree familial social capital. It is often unspoken and enabled as well as constrained by personal reputation and social standing—that is, by how much respect and trust one enjoys.
5. Workshop: Co-chaired by José Rivera and Quita Ortiz in which scholars and activists were invited to formulate and propose an agenda of research and policy based on new insight. Invited panelists: Paula García, Estevan Arellano, Miguel Santistevan, Arnie Valdez, and Manuel Montoya. CNH team: Sam Fernald, Carlos Ochoa, and Sylvia Rodríguez.
6. Orlove and Caton (2010) proposed this tripartite framework.

## REFERENCES

- Bourdieu, P. 1984. *Distinction: A social critique of the judgement of taste*. Cambridge, MA: Harvard University Press.
- Cox, M., and J.M. Ross. 2011. Robustness and vulnerability of community irrigation systems: The case of the Taos valley acequias. *Journal of Environmental Economics and Management*, 61, 254–266.
- Fernald, A.G., and S.J. Guldán. 2006. Surface water-groundwater interactions between irrigation ditches, alluvial aquifers, and streams. *Reviews in Fisheries Science*, 14, 79–89.
- Fernald, A.G., T.T. Baker, and S.J. Guldán. 2007. Hydrologic, riparian and agroecosystem functions of traditional acequia irrigation systems. *Journal of Sustainable Agriculture*, 30, 147–171.
- Fernald, A.G., V. Tidwell, J. Rivera, and J. Wilson. 2009. *Acequia water systems linking culture and nature: Integrated analysis of community resilience to climate and land-use changes* [research proposal]. National Science Foundation (Number 1010516), 3.
- Fernald, A., J. Rivera, S. Rodríguez, V. Tidwell, C. Ochoa, Q. Ortiz, and S. Guldán. 2014. Connectivity of coupled hydrologic and human systems as the basis of resilience in traditional irrigation communities in New Mexico. Paper presented at Conference on Irrigation, Society, and Landscape: Tribute to Thomas F. Glick, Valencia, Spain, September 2014, pp. 418–428.



- Fernald, A.G., V. Tidwell, J. Rivera, S. Rodríguez, S. Guldán, C. Steele, C. Ochoa, B. Hurd, M. Ortiz, K. Boykin, and A. Cibils. 2012. Modeling sustainability of water, environment, livelihood, and culture in traditional irrigation communities and their linked watersheds. *Sustainability*, 4, 2998–3022.
- Linton, J. 2010. *What is water?* Vancouver: University of British Columbia Press.
- Linton, J., and J. Budds. 2014. The hydrosocial cycle: Defining and mobilizing a relational-dialectical approach to water. *Geoforum*, 57, 170–180.
- Liu, J., T. Dietz, S.R. Carpenter, C. Folke, M. Alberti, C.L. Redman, S.H. Schneider, E. Ostrom, A.N. Pell, J. Lubchenco, W.W. Taylor, Z. Ouyang, P. Deadman, T. Kratz, and W. Provencher. 2007. Coupled human and natural systems. *AMBIO: A Journal of the Human Environment*, 36, 639–649.
- McConnell, W.J., J.D.A. Millington, N.J. Reo, M. Alberti, H. Asbjornsen, L.A. Baker, ... and J. Liu. 2011. Research on coupled human and natural systems (CHANS): Approach, challenges, and strategies. *The Bulletin of the Ecological Society of America*, 92, 218–228.
- Orlove, B., and S.C. Caton. 2010. Water sustainability: Anthropological approaches and prospects. *Annual Review of Anthropology*, 39, 401–415.
- Ostrom, E., and T.K. Ahn. 2007. The meaning of social capital and its link to collective action. In G.T. Svendsen and G.L. Svendsen (Eds.), *Handbook on social capital: The troika of sociology, political science, and economics* (pp. 17–35). Cheltenham, UK, and Northampton, MA: Edward Elgar Publishing.
- Trawick, P. 2003. *The struggle for water in Peru: Comedy and tragedy in the Andean commons*. Stanford, CA: Stanford University Press.
- Trawick, P., M.O. Reig, and G.P. Salvador. 2014. Encounters with the moral economy of water: Convergent evolution in Valencia. *WIREs Water*, 1, 87–110.
- Turner, B., V. Tidwell, A. Fernald, J. Rivera, S. Rodríguez, S. Guldán, C. Ochoa, B. Hurd, K. Boykin, and A. Cibils. 2016. Modeling acequia irrigation systems using system dynamics: Model development, evaluation, and sensitivity analyses to investigate effects of socio-economic and biophysical feedbacks. *Sustainability*, 8, 1019.



# The Roots of Community in the Northern Rio Grande: Acequia Mutualism, Cultural Endurance, and Resilience

José A. Rivera

## INTRODUCTION

The community-based *acequias* of the northern Rio Grande are the oldest water management institutions of European origin in the United States. These irrigation systems date to the time of the first Spanish settlement in the northern frontiers of New Spain with the first Juan de Oñate colony in 1598 at the confluence of the Rio Grande and the Rio Chama. At the time, the provinces of the north encompassed a vast semiarid territory rich in natural and mineral resources but short on water supply. Here the Rocky Mountain range of Colorado joins the great Chihuahuan desert from the south and the Llano Estacado from the plains of Texas on the east. The bioregion is drained principally by the *Río del Norte*, now depicted on maps as the Rio Grande heading south from Creede, Colorado, to El Paso, Texas.

Due to conditions of aridity, Spanish colonization policies required that officials of the crown locate their communities in the vicinity of water resources essential for permanent occupation. The irrigation technology employed by the waves of *pobladores* (settlers) was gravity flow of surface water diverted from rivers through a system of earthen canals known as acequias. The settlers worked mutually to build these irrigation networks throughout the present southwestern United States: Texas, New Mexico, Colorado, Arizona, and California. However, it was in *La Provincia de San Felipe del Nuevo México* along the upper Rio Grande that settlement policies were the most effective, particularly with regard to the establishment of civilian towns and agricultural colonies. Once constructed, the local *acequia de común* (commons ditch) wedded the appropriators into a hydraulic society, as often expressed in the phrase, “Water is the lifeblood of the community,” thus constituting an important component of **mutualism/mutualismo** that still exists today.

By mutualism, we refer to the **social capital** of a community that fosters a relationship of interdependence based on mutual trust and reciprocity for the common good. Prior to the annexation of New Mexico and Colorado by the United States, many forms of community mutualism coexisted in settlements along the northern Rio Grande, and together they continue to perpetuate a sense of place

while maintaining a cultural heritage rooted in the principle of *ayuda mutua*, or mutual help for survival. Among others, these organizations include the acequias de común, *cofradías de penitentes*, and the *sociedades mutualistas* (mutual aid societies) (Rivera, 2010).

The *cofradías* were religious brotherhoods where Catholic men associated for purposes of religious worship, for rituals of penance during Holy Week, and to help others by performing acts of charity: ministering to the sick and elderly, providing food to needy families, arranging funeral and burial ceremonies, and assisting widows and orphaned children. The *cofradías de penitentes* surfaced at a time when spiritual administration was too distant from the locus of village life in the region. Out of necessity, these *hermanos* (members, brothers) developed autonomous societies outside the hierarchy of the Catholic Church as they undertook religious practices of their own native design and established constitutional rules of self-government. In addition, they built private chapels (*moradas*) that also served as meeting halls to conduct business affairs and develop various programs of charity to villagers in need.

Later, a lay version of the *cofradías* emerged as *sociedades mutualistas*. They performed similar functions of community service and benevolence but did not associate for religious purposes. Instead the *sociedades mutualistas* added new forms of mutual aid, such as offering low-cost life insurance and economic assistance in times of illness, granting small loans, and, in some cases, combatting wage and racial discrimination of workers in the railroad, mining, and other resource extractive industries. For the provision of social services, they designed local projects of assistance (*obras de caridad*), recorded their rules and minutes in journals, displayed their membership ribbons or *devisas* at public ceremonies and conventions, and at the end of life, they held vigil over the deceased *hermanos*, dug their graves, paid their respects, and then provided financial help to the widows, orphans, and other survivors.

A key principle for each type of mutual union was the idea of pooling resources to help protect members from poverty, unemployment, and healthcare emergencies, and to lessen the burdens of funeral expenses when members

passed away. At the core was a belief that help should come from the people in the community, *de nuestro pueblo*, all for the good of the society and advancement of the common welfare. For an in-depth analysis of mutualismo, in this chapter we will explore the motives for collective action that resulted in the formation of the community acequias. At the end, we will present mutualism and other key factors of resilience that account for continuity of the northern Rio Grande acequia culture.

### ACEQUIAS DE COMÚN: COMMUNITY IRRIGATION DITCHES

Led by Juan de Oñate in 1598, caravans of Spanish-Mexican settlers and Mexican Indian allies came up the Camino Real from Mexico City, traversed the *Jornada del Muerto* north of *El Paso del Norte*, and finally reached the confluence of the *Río Grande del Norte* and the *Río de Chama* (Martínez Saldaña and Rivera, 2008). Here, they searched for perennial streams of water fed by distant snowpacks in the alpine sierras to the north. Without the aid of survey instruments or modern tools, the early settlers engineered irrigation works superimposing *zanjas* (earthen canals) on the desert landscape, all with collective human labor. The first step, as instructed by the laws issued by the Spanish crown, was to locate a bend in the river or another suitable feature to build a diversion structure from which to capture water and turn it into ditches on one or sometimes both banks of the natural watercourse. Constructed of locally available materials, such as forest timbers, brush, and rocks, these irrigation works defined the landscape and demarked the boundaries for irrigation off the main canal and its laterals for several miles downstream. Thus, acequias extended the riparian zone beyond the narrow confines of the natural channels. The successive waves of settlers into the tributaries of the Rio Grande replicated these technologies of construction and irrigation methods, which fostered the growth of agrarian communities along the *Camino Real de Tierra Adentro* (Royal Road of the Interior Lands) from El Paso del Norte to Santa Fe and later to the Taos Basin and parts of southern Colorado (Peña, 1998).

From the time of the first Hispanic settlement in the northern Rio Grande, hydrologic function and social organization in the valley bottomlands have been inextricably linked to the upland bioregions in the sierras of the *Sangre de Cristo* and other mountain ranges. The forested lands included meadows and pastures that supported livestock during the summer months and were also places to harvest wood as a source of fuel. During the winter months, the sierras were critical to the formation of snowpack that in the early spring provided the runoff necessary to irrigate lands down in the valley. Water supply was the key to settlement policies under the Spanish Laws of the Indies, a resource condition that necessitated the formation of “corporate villages” as an underlying structure in human organization (Van Ness, 1991). As incentives to the waves of settlers

coming north along the Camino Real de Tierra Adentro from the Central Valley of Mexico, the Spanish crown offered *mercedes de tierra* (land grants) to *pobladores principales* (settlement leaders) and others in family groups so that they might establish permanent agricultural colonies in the vast stretches of desert land in the *Provincia de San Felipe del Nuevo México*.

Once these lands were conveyed in a formal possession ceremony by the Provincial Governor or the district *alcalde* (mayor), governance was placed in the hands of the community. The settlers themselves were responsible for organizing a local government, usually into a *consejo de vecinos*, a council of neighbor/citizens selected by the community to set up rules for the sharing of resources and, importantly, to form *mancomunidades* (communal labor) for the construction and maintenance of irrigation canals or acequias (Ebright, 1996; Meyer and Brescia, 1998). These collective projects were early forms of mutualism, a process that would be replicated later for other needs and problems that arose. Administration of land and water resources thus made for a corporate social organization and a set of “tightly bound social relations” adapted to the rugged and inhospitable environment in the high mountain upland terrain of Northern New Mexico and later the San Luis Valley of Colorado (Gonzales, 2003).

The *alcalde* granted the forested lands as *ejidos* or commons for use by all villagers for livestock grazing, hunting, and other uses. In addition, he granted each settler farm tracts or *suertes* in the valley floor on which to build a house and begin the process of clearing the land for cultivation of crops both for home subsistence and for livestock raising, a distinct and essential part of the mixed farm and ranch economy that prevails to this day. This process of *repartimiento de tierras* (land partitions) was repeated by the landowners themselves when it came time to build and then administer the acequia system. Mutualism was a constant process of making social arrangements across the landowner neighbors, such as devising plans (*el reparto*) to distribute and share water, elect officers, establish rules for water allocation, resolve internal conflicts and disputes, and to organize and conduct the annual *limpia*, or ditch cleaning, needed at the start of every irrigation season. For the most part, these water customs and traditions continue to the present.

Acequia technologies and irrigation methods employed by the Hispanic settlers in the new province were melded from diverse sources. Historians agree that these antecedents included the irrigation practices common to the arid regions in the south of Spain, particularly Andalusia, Castilla, and Valencia, and were based on traditions from the Roman period along with the superimposition of Arabic customs and techniques during the seven centuries of occupation of Spain by Muslims from North Africa and the Middle East. Also important was the influence of Pueblo Indian agriculture as observed by early Spanish explorers and expeditions

into the Rio Grande basin and the irrigation horticulture of Mesoamerica brought by Mexican Indians who accompanied the Spanish caravans along the *Camino Real de Tierra Adentro* (Martínez Saldaña, 2011).

During the Spanish colonial period (1598–1821), a community of landowners owned and managed water resources. All of the landowners irrigated from a single main canal similar to the organizational arrangements of *la comuna* of medieval Valencia in southern Spain. According to Glick, the comuna was the basic irrigation unit that distributed water, maintained the canal system, and elected a *cequier* (head water official) to administer the *ordenanzas* (rules) of the canal. In structure, these Spanish irrigation communities adopted institutional forms and executive procedures similar to the craft guilds and their parallel religious confraternities that pre-existed just after the Christian Reconquest. The guilds were the most immediate model for the Valencian farmers to adopt because the tribal governance of the Muslims based on clans and other kinships would not have been the norm to follow (Glick, 1970, 2003).

In New Mexico, the initial settlers also organized themselves as a community of irrigators; the owners of property with irrigable lands collectively viewed themselves as *el pueblo* or town. Each acequia infrastructure was built as a **commons** where the irrigators formed agreements to work collectively, a union of citizens or mancomunidad. Given the harsh, semiarid environment, the ditch was an element of sheer necessity for the establishment and sustenance of the entire village. When a land grant was issued, settlers were required to construct an irrigation system for the common welfare, as in the decree of 1794 establishing the *San Miguel del Bado Land Grant*. Here the *Alcalde de Santa Fe* instructed the 52 petitioners, “That the construction of their Plaza, as well as the opening of the ditches, and all other work that may be deemed proper for the common welfare shall be performed by the community with that union which in their government they must preserve” (Leonard, 1970). Construction of the diversion dam upstream and the *acequia madre* (main canal) through and below the community was only the first step; annually, repairs would be needed, as would the ritual of cleaning the acequias early each spring at the start of the irrigation season (Rivera, 1998; Rodríguez, 2006).

In Meyer and Brescia’s (1998) view, the mutual aid function of the public works labor force for construction of the canal was primary and akin to the religious societies of the times:

Over time the *mancomunidad*...grew from an instrument of physical survival to one of cultural survival. Just as the ditch itself tied the fields together, the association tied the rural neighborhood together, reinforcing *compadrazgo*, imparting to each village a distinct identity, and offering itself as a mechanism for mutual aid during crises or times of need. In essence it blended the

cultural and the material into a kind of secular *cofradía*, a confraternity that formed the nucleus of rural life in Hispanic New Mexico.

Loose and informal, this mutual union of irrigators laid the foundation for the evolution of the community **acequia associations**, which were recognized and empowered later, during the 1890s, in the American territorial laws of New Mexico as corporate bodies. Of necessity, and key to the success of each irrigation system, the community settlers did not adhere to a prescribed set of regulations from a central authority. Instead they negotiated institutional arrangements among the collective that they called *arreglos*, operational rules that were specific to the water delivery requirements of the shared canal and its laterals. The taking of water during the initial *saca de agua* (digging out of the ditch) carried forward into the local customs and traditions for water distribution, the operations and maintenance of the irrigation works, and the annual *limpia* during the early spring just before the expected runoff season. This self-organized enterprise wedded the irrigators into a shared institution for water management that bonded them as a hydraulic society, a living culture of water based on cooperation and mutualism. As noted by Glick (2013), the acequias of New Mexico persist as consensual communities, autonomous institutions with self-governance based on guild-like administrative practices and operating procedures determined by the *parciantes* (member irrigators) themselves and not by outside officials.

Eventually, the methods and practices that worked effectively in one locale were replicated in other settlements along the northern Rio Grande from the Santa Cruz Valley, westerly along the Rio Chama, north to the Taos Basin, and eventually to the San Luis Valley in southern Colorado. These acequia watercourses in turn served as *caminos de agua* (water roads) by extending the *Camino Real* into the tributaries and creeks of the upper Rio Grande wherever pockets of arable land could be found and transformed into agrarian settlements. Today there are about 800 local, individual acequias in New Mexico and about 75 in southern Colorado. In New Mexico, the largest concentration of acequias is located in Rio Arriba, Taos, Mora, San Miguel, Santa Fe, and Guadalupe Counties. The acequias have maintained and preserved the irrigation customs and helping traditions of earlier times. The *Acequia Madre de La Joya*, for example, continues to follow its “*Reglas y regulaciones para el gobierno y manejo de la acequia de comunidad*” (Rules and Regulations for the Governance and Management of the Community Ditch), to include a system for the assignment of daily labor responsibilities called *días de fatigas* during the annual cleaning of the acequia, with a special provision that exempts “*las personas que estén incapacitadas o mujeres solas viudas*” (handicapped persons or women who are widowed) (Acequia Madre de La Joya, 1942).



In contemporary times, the local acequia associations organize educational programs, cultural events, and religious activities at the watershed and regional levels; publish newsletters; provide technical assistance workshops; and hold an annual meeting of the **Congreso de las Acequias**, which is convened by the statewide, non-profit New Mexico Acequia Association. In Colorado, the acequias are affiliated into the Sangre de Cristo Acequia Association, with the aim of protecting water rights and the unique governance structures of acequias. Local acequias organize community celebrations, such as the ritual blessing of the **ojito** (spring) at *San Antonio de Padua* near Albuquerque that includes a mass and **matachines** (traditional dance portraying the triumph of Christianity) procession from the parish church to the site of the spring well. On the feast day of **San Ysidro**, one of the Taos acequias celebrates the patron saint of farming by holding a **novena** and evening mass at their chapel, followed by a procession along the parish roads and into the irrigated fields to bless the sacred landscape of springs, ditches, corrals, homes, the chapel, and other religious shrines. As documented by Sylvia Rodríguez (2006), this route symbolically encircles both the lower *Rio Grande del Rancho* watershed and the boundaries of the parish of *San Francisco de Asís*.

Community rituals and collective responses to common needs and problems made possible the continuity of acequia culture into the twenty-first century. In the northern Rio Grande bioregion, the people have survived for centuries and have endured countless threats, challenges, and turbulence in the environment. Ernest Atencio (2004) said it best, and eloquently, when he wrote:

In the mountains and mesas of northern New Mexico and southern Colorado, a land-based Indo-Hispanic village culture persists against all odds. For over four centuries, these isolated ranching and farming communities have survived the rigors of frontier life in the farthest corner of the Spanish kingdom, generations of raiding by nomadic tribes, rebellions, wars and conquest, the vagaries of weather, dispossession of community lands, and desperate poverty. But they have done more than simply survive. A distinctive culture has developed in the region that remains a dynamic and defining presence today. And after centuries of continuity and adaptation, rural villagers have acquired a powerful sense of belonging, a rooted knowledge and reverence for their homeland that has become rare in the modern world.

The acequia de común is a distinct form of collective action that shares a number of key characteristics with the *cofradías de penitentes* and *sociedades mutualistas*: local governance, adaptation, and solidarity of the group. All three forms have survived for one, two, and up to more than four centuries that includes periods of rapid social change, transformations in the legal-political environment,

and a barrage of pressures brought forth by the forces of modernity in a postindustrial society. The successes of one mutual aid form helped to create others, as new problems surfaced in the throes of change and the need for self-preservation of community and cultural identity in the land of the ancestors, or *nuestro pueblo*. Absent governmental intervention, social relief depended on the mobilization of resources from within the agrarian villages based in large part on the traditions of *mutualismo*, which were embedded in a culture of self-help, **la cultura de ayuda mutua** (Rivera, 2010).

## COMMUNITY MUTUALISM

*Irrigation is man's response to drought; by this means he reduces radically the uncertainty that nature presents to human settlement in an inhospitable environment. To succeed for any length of time, to capture and distribute available water, and to control the amount of land placed under irrigation, farmers must develop self-discipline and a high level of community organization.* (Maass and Anderson, 1978)

How are the community-based acequias organized, and do they evidence the requisite features of sustainability posited by Maass and Anderson (1978) in terms of self-discipline and a high level of community organization? Do the acequias operate under rules of popular participation and local control as well as the principles of justice, equity, and internal conflict resolution? Will the acequia culture of the northern Rio Grande endure?

For governance, the *parciantes* in each acequia elect three **commissioners** and a **mayordomo** (ditch manager) who have decision authority and local control of water management within the service area of their acequia system. This feature of local control is a key factor in their ability to adapt to seasonal and climatic changes, especially during times of low flows in the stream or reductions of snowpack conditions in the headwater's source. This **adaptive capacity** of the acequia is largely a social component, part of the institutional robustness of the system (Cox, 2010). In most watersheds, the acequias are the most upstream diversions in the system, and therefore the officers can respond and adapt quickly to seasonal changes in streamflow. During times of water scarcity or years of prolonged drought, for example, the acequia can modify the system of turns for water delivery according to customs and traditions of **repartimiento** (water sharing), **auxilio** (emergency water), and allocation of **sobrantes** (surplus waters). Agreements on how to divide the water within and across acequias may be reviewed and altered to fit existing conditions in the stream season to season. Acequias make decisions of this kind at open meetings of the *parciantes* to ensure transparency and compliance with any new or modified rules of water distribution. When violations occur, the acequias impose fines, curtail water, or take other appropriate measures to enforce and uphold the rules on an impartial basis. In all of these respects, the acequia landowners

control their own destinies by acting collectively, the dominant characteristic found in case studies of successful irrigation communities operating in other world desert environments (Maass and Anderson, 1978)

The ability of the acequia community to recover from natural changes and other stressors in the environment is an indicator of system resilience. Their discretionary authority to alter the operating procedures by tightening the rotation of turns allows the officers to respond to ecosystem disturbances as they arise. Like other traditional irrigation systems around the world, the acequias of the northern Rio Grande are well adapted to their environments and would have disappeared long ago were they not. By now, they have survived as water management institutions under three sovereigns and each sovereign's laws pertaining to water administration: colonial Spain, the Republic of Mexico, and the United States. In this regard, the acequias measure up to the widely accepted design principles of "long enduring, self-organized irrigation institutions" (Ostrom, 1992). They also exemplify what Mabry (1996) describes as self-governing, collective choice institutions that manage commonly held water resources under conditions of relative resource scarcity. Canals and communities of this type "are held together by shared ecological risks, mutual economic interests, and collective investments in the means of production" (Mabry, 1996). To Mabry, these small-scale organizations are sustainable due to a number of characteristics: compliance with rules that spread risk, level disparities, and resolve conflicts. The acequias of the northern Rio Grande conform to Mabry's definition of locally governed institutions in that they "are exclusive in membership, territorial in defense of resources, resistant to outside interventions, and resilient in the face of change" (Mabry, 1996).

In his many decades of studying the cultural meaning of ancient hydraulic landscapes worldwide, Glick (2006) advocates for the preservation of acequia landscapes as significant human artifacts that have been stable, long-term providers of food. Following Glick's analysis, traditional agricultural systems are knowledge-intensive, and 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, climatic conditions, crops, and water requirements for every niche suitable for agriculture. The social cohesion of the irrigators derives from the values encoded in the operational rules of water sharing, namely equity, justice, and local control. As is the case with other long-enduring common property regimes in the world, the acequia parciales of the northern Rio Grande will continue their participation so long as their collective actions ensure that their benefits and rights to irrigation water will remain intact into future years. In practical terms this means access to water at the point of delivery, meaning the *compuertas* (headgates) that take water into their individual parcels. In the prototypical acequia, the diversion on the stream along with the parcial headgates

are the key physical structures, but of equal importance is the fact that compuertas tie each landowner irrigator to the social arrangements for water management of the hydrological system as a whole.

## CONCLUSIONS

Many factors have contributed to acequia resiliency, but the concept of mutualismo, reciprocal mutual aid, has to be included among the essential foundations of community cohesion and sustainability. In times of hardship or other needs, voluntary associations mobilized local resources and bonded the *vecinos* into a collective identity deeply rooted in the land, a place, region, and homeland they called nuestro pueblo (Rivera, 2010). Rituals, democratic participation in governance, and continuity of culture have maintained solidarity and retained the identity of the land-based people of the region, the essence of *querencia* described to perfection by Juan Estevan Arellano (1997) when he wrote, "*El que pierde su tierra, pierde su memoria*" (He who loses his land, loses his memory). *Querencia* is what anchors people to the land, and this attachment in turn informs and inspires mutualism across neighbors and kin who live in the same place. The sense of *confianza* (reciprocal trust) in turn connects residents with each other knowing that they can all expect mutuality in social exchanges, a critical part of the culture since the period of colonial settlement (Velez-Ibanez, 2010). After a lifetime of learning about wisdom of the land and knowledge of the water from his elders and mentors, Arellano, the former mayordomo of the *Acequia Junta y Ciénaga* on the Rio Embudo, concludes that healthy bioregions and strong rural economies depend on safeguarding land, water, and people as a common interest and not as the private property of individuals (Arellano, 1997, 2014).

The religious brotherhoods of penitentes and the secular sociedades mutualistas of the last century have declined in number, but the heritage of mutualism thrives in the hundreds of *riegos ancestrales* (ancestral irrigation systems) that survive in the acequia landscapes of New Mexico and southern Colorado (Martínez Saldaña, 2011). This heritage includes multiple patterns of collective labor and reciprocity that take place at the start of and throughout the yearly irrigation cycle: the social organization for water management to accomplish the common objective of irrigation from a shared water source; repeated actions of mutual help that keep the organizational structure robust and prevent its collapse; reliance on elders with knowledge and experience to transmit customs and traditions to new generations; rituals and use of the Spanish language that bond the community, such as the annual ditch cleaning in the early spring and in some communities religious ceremonies and processions to bless water sources and other sacred landscapes on *día de San Ysidro* or feast days for the village patron saint; and a sense of communal responsibility for those unable to tend to the



acequia duties, such as widows or handicapped persons who are exempt from work days to clean or repair the ditch infrastructure. Together, these bonds of mutuality and social participation in events that celebrate the culture reinforce identity not as an individual trait but as a regional people with a common history and shared institutions, a form of corporatism that stresses membership in the group as the basis of interpersonal relations (Briggs, 1988).

Will the acequias de común survive the multitude of stressors working against small-scale agriculture not only in the northern Rio Grande but in the global economy as well? Are there “tipping points” (hydrologic, economic, social) that are beyond the capacity of the acequias to resolve, and can these threats be averted? Solidarity, community cohesion, and mutualism are important elements of system renewal to counter threats that may surface periodically, but in the long term, customary practices are knowledge-based and need to be handed down by the elders in the native Spanish dialect of the *parciantes* and *mayordomos*, not just in the dominant English language. Cultural practices, along with environmental knowledge, are embedded in the lexicon of the acequia, and these concepts do not translate readily (Arellano, 2013, 2014). Examples of social memory and local knowledge held by the elders include how to classify the anatomy of an acequia from the headwaters in the sierra down to the *presa* and from there to the network of main canals and laterals carved into the valley bottomlands, how and when to open and close *compuertas* along the acequia and into the *desagüe* (drainage) channel for return flow to the river, how to design *repartimientos* and other flow sharing procedures that are equitable and adaptable to environmental conditions during wet and dry seasons, and how to move with the water once diverted from the acequia madre into the *linderos* (laterals) that carry water into the *huertos* (orchards), *milpas* (fields), and *vegas* (pastures) (Arellano, 2014).

The best way to preserve the acequias is to keep them alive as food producing systems, and that we teach, learn, and relearn the lexicon of the acequia in native Spanish as a heritage language alongside the use of English. Language recovery programs should be instituted in New Mexico and southern Colorado at all levels of education, K–12 plus community colleges and universities. We conclude with a set of propositions that characterize system resiliency of acequia governance that may hold the key to adaptation when new challenges emerge in future scenarios of unexpected change. These conclusions stem from multidisciplinary research reported as chapters in this book.

(a) The acequia culture is based on a reciprocal relationship between irrigation and community that creates a sense of place, attachment to the land, and a shared cultural identity based on membership in the corporate group.

- (b) Mutualism is a core principle that is embedded in the community structure for maintaining traditional practices with respect to labor contributions, water sharing, and other system requirements.
- (c) Mutual trust results in cooperation over water sharing when acequias are confronted with drought or other stressors from outside the community.
- (d) Customary practices combine hydrologic and socio-cultural strategies encoded in the acequia culture to respond collectively to snow melt releases in the spring and variable precipitation during the summer months.
- (e) Autonomy of the decision-making structure in acequia governance permits rapid adjustments in the operational rules and practices of each acequia when warranted by changing environmental conditions of wet or dry seasons.
- (f) Participation in acequia rituals will endure as long as the hydro-physical system delivers water to the *compuerta* of each *parciante*, and as long as the benefits of membership, both economic and non-economic, outweigh or at minimum are in balance with the costs of participation.
- (g) Collective knowledge of local ecology and customary practices in Spanish and English languages is a vital component of social capital for transmission to the next generation, a process essential to the continuity of acequia agriculture and culture.

In the research arena, we need to learn more about how to strengthen the capacity of acequias to respond to stressors that threaten to erode mutualism. In recent times, regional population growth, urbanization, a changing demographic profile, economic development, cyclical drought, and other complex factors have adversely impacted acequia communities. **System dynamics modeling** offers a new interdisciplinary platform for integrating linkages that affect acequia function and vitality across a number of driving variables: hydrology, ecology, society, and economics. The more we understand the feedbacks, the closer we get to the design of interventions that will preserve acequia mutualism as one of the main principles that sustains community management of natural resources. The “Connection and Integration: A Systems Approach to Exploring Acequia Community Resiliency” chapter in this volume describes the system dynamics approach and how community mutualism plays an important role in sustaining linkages between natural and human systems that increase resilience to stressors. The study of mutualism and how it evolved in the acequia culture provided the **Dynamics of Coupled**

**Natural and Human Systems Program (CNH)** modelers and the multidisciplinary research team as a whole with a way to integrate mutualism as a vital component of social capital in the community.

## ACKNOWLEDGMENTS

The early work that led to the development of this paper came from a presentation at the “4th Annual *Celebrando las Acequias*: Water + Resilience,” sponsored by the Arid Lands Institute of Woodbury University and hosted by Juan Estevan Arellano, at Embudo Mission, Dixon, New Mexico, June 10–12, 2011. Additional work was conducted from 2008–2015 and supported by research grants made by the National Science Foundation to New Mexico EPSCoR (award #0814449) and to New Mexico State University (award #101516), with a subaward to the Center for Regional Studies at the University of New Mexico. Other collaborators in the NSF research included the New Mexico Institute of Mining and Technology, Sandia National Laboratories, and the New Mexico Acequia Association.

## REFERENCES

- Acequia Madre de La Joya. 1942. *Reglas y regulaciones para el gobierno y manejo de la acequia de comunidad* [unpublished paper].
- Archuleta, R.E. 2003. *Land of the Penitentes, land of tradition*. Pueblo West, CO: El Jefe Publisher.
- Archuleta, R.E. 2007. *Penitente renaissance: Manifesting hope*. Pueblo West, CO: El Jefe Publisher.
- Arellano, J.E. 1997. La querencia: La raza bioregionalism. *New Mexico Historical Review*, 72, 31–37.
- Arellano, J.E. 2013. New Mexico acequia workshop presentation at *Acequias and the future of resilience in global perspective*, Las Cruces, NM, March 2–3, 2013. Retrieved May 20, 2014, from <http://www.culturalenergy.org/listenlinks.htm>
- Arellano, J.E. 2014. *Enduring acequias: Wisdom of the land, knowledge of the water*. Albuquerque: University of New Mexico Press.
- Atencio, E. 2000, November. Environmental justice and public lands ranching in Northern New Mexico. The *Quivara Coalition* [newsletter], vol 1, no. 1. <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.453.8485&rep=rep1&type=pdf>
- Briggs, C.L. 1988. *Competence in performance: The creativity of tradition in Mexicano verbal art*. Philadelphia: University of Pennsylvania Press.
- Cox, M. 2010. *Exploring the dynamics of social-ecological systems: The case of the Taos valley acequias* [doctoral dissertation]. Retrieved from [https://www.researchgate.net/publication/42766398\\_Exploring\\_the\\_Dynamics\\_of\\_Social-Ecological\\_Systems\\_The\\_Case\\_of\\_the\\_Taos\\_Valley\\_Acequias](https://www.researchgate.net/publication/42766398_Exploring_the_Dynamics_of_Social-Ecological_Systems_The_Case_of_the_Taos_Valley_Acequias)
- Darley, A.M. 1974. *The Mexican American: The Penitentes of New Mexico*. New York, NY: Arno Press.
- Ebright, M. 1996. Breaking new ground: A reappraisal of governors Vélez Cachupín and Mendinueta and their land grant policies. *Colonial Latin American Historical Review*, 5, 195–233.
- Fernald, A., V. Tidwell, J. Rivera, S. Rodríguez, S. Guldán, C. Steele, C. Ochoa, B. Hurd, M. Ortiz, K. Boykin, and A. Cibilis. 2012. Modeling sustainability of water, environment, livelihood, and culture in traditional irrigation communities and their linked watersheds. *Sustainability*, 4, 2998–3022.
- Glick, T.F. 1970. *Irrigation and society in medieval Valencia*. Cambridge, MA: Belknap Press of Harvard University Press.
- Glick, T.F. 2003. Thin hegemony and consensual communities in the medieval crown of Aragon. In M. Barcelo et al. (Eds.), *El feudalisme comptat i debatut: Formació i expansió del feudalism Català*. Valencia, Spain: Universitat de València.
- Glick, T.F. 2006. Historical status and cultural meaning of historic hydraulic landscapes: Oasis. Paper presented at First International Congress on Oasis and Sustainable Tourism, Elche, Spain, December 15, 2006.
- Glick, T.F. 2013. New Mexico acequias as living simulacra of medieval peninsular irrigation communities. Paper presented at 44th Annual Meeting of the Association for Spanish and Portuguese Historical Studies, Albuquerque, NM, April 4–7, 2013.
- Gonzales, P.B. 2003. Struggle for survival: The Hispanic land grants of New Mexico, 1848–2001. *Agricultural History*, 77, 293–324.
- Knowlton, C.S. 1969. Changing Spanish-American villages of New Mexico. *Sociology and Social Research*, 53, 462.
- Kutsche, P., and D. Gallegos. 1979. Community functions of the Cofradía de Nuestro Padre Jesús Nazareno. In P. Kutsche (Ed.), *The survival of Spanish American villages*. Colorado Springs: Colorado College.
- Lamadrid, E.R. 2008. Rutas del corazón: Pilgrimage and cultural commerce on the Camino Real de Tierra Adentro. *New Mexico Historical Review*, 83.
- Leonard, O.E. 1970. *The role of the land grant in the social organization and social processes of a Spanish-American village in New Mexico*. Albuquerque, NM: Calvin Horn Publisher, Inc.
- Maass, A., and R.L. Anderson. 1978. *...and the desert shall rejoice: Conflict, growth and justice in arid environments*. Cambridge, MA: MIT Press.
- Mabry, J.B. 1996. *Canals and communities: Small-scale irrigation systems*. Tucson: University of Arizona Press.
- Martínez Saldaña, T. (General Ed.). 2009. *Riegos ancestrales en Iberoamérica. Técnicas y organización social del pequeño riego*. In T. Martínez Saldaña, J. Palerm, M. Castro, and L. Perei (General Ed. and Regional Eds.). Colegio de Postgraduados and Mundi Prensa México, S.A. de C.V.

- Martínez Saldaña, T., and J.A. Rivera. 2008. Cofradías y mutualidades en el norte de la Nueva España: La organización en torno a los sistemas de riegos coloniales. *Boletín del archivo histórico del agua*, 13, 8–16.
- Meyer, M.C., and M.M. Brescia. 1998. The Treaty of Guadalupe Hidalgo as a living document: Water and land use issues in Northern New Mexico. *New Mexico Historical Review*, 73.
- Ostrom, E. 1992. *Crafting institutions for self-governing irrigation systems*. San Francisco, CA: ICS Press.
- Peña, D.G. 1998. Cultural landscapes and biodiversity: The ethnoecology of an Upper Rio Grande watershed commons. In V.C. de Baca (Ed.), *La gente: Hispano history and life in Colorado*. Denver: Colorado Historical Society.
- Rivera, J.A. 1998. *Acequia culture: Water, land, and community in the Southwest*. Albuquerque: University of New Mexico Press.
- Rivera, J.A. 2009. *La cultura de la acequia: Agua, tierra y comunidad en el Suroeste de los Estados Unidos de América*. Valencia, Spain: University of Valencia Press.
- Rivera, J.A. 2010. *La sociedad: Guardians of Hispanic culture along the Río Grande*. Albuquerque: University of New Mexico Press.
- Rodríguez, S. 2006. *Acequia: Water sharing, sanctity, and place*. Santa Fe, NM: School of Advanced Research Press.
- Santistevan, M.A. 2003. *Trends in maize diversity of Northern New Mexico: A regional synopsis and case study in acequia agriculture* [master's thesis]. University of New Mexico.
- Sargent, F.O., P. Lusk, J.A. Rivera, and M. Varela. 1991. *Rural environmental planning for sustainable communities*. Washington, D.C.: Island Press.
- Steele, T.J., and R.A. Rivera. 1985. *Penitente self-government: Brotherhoods and councils, 1797–1947*. Santa Fe, NM: Ancient City Press.
- Van Ness, J.R. 1991. *Hispanos in Northern New Mexico: The development of corporate community and multi-community*. New York: AMS Press.
- Velez-Ibanez, C.G. 2010. *An impossible living in a transborder world: Culture, confianza, and economy of Mexican-origin populations*. Tuscon: University of Arizona Press.
- Weigle, M. 1970. *The Penitentes of the Southwest*. Santa Fe, NM: Ancient City Press.

# Acequia Ecosystems

Kenneth G. Boykin, Elizabeth A. Samson,  
and Guillermo Alvarez

---

## INTRODUCTION

### Ecosystems

Ecosystems consist of the biological community and the associated physical and chemical environment (Primack, 2006). Ecosystems can be as small as a temporary pool where toads and invertebrates reproduce or as large as the entire Chihuahuan Desert. Plants and animals that are associated with each ecosystem can be identified and enumerated, and the physical and chemical characteristics of that system can be described. Ecosystems can be dynamic, changing from season to season and year to year. For example, flooding affects **riparian ecosystems** when flood waters scour river systems and remove vegetation (Naiman et al., 1993). Changes can also be more subtle, such as woody plant encroachment into savannas from woodlands and forests (Van Auken, 2009). Ecosystems are often the focus of conservation because properly managed ecosystems will benefit all or most of the species that inhabit them (New Mexico Department of Game and Fish [NMDGF], 2006).

In the Desert Southwest, riparian ecosystems are important ecosystems that traverse the landscape. They are associated with the streams and rivers that dissect the dryer uplands. Riparian areas represent less than 2% of the overall area in the region, but they are crucial to **biodiversity** (Szaro, 1989). These areas host and maintain vegetation communities that support numerous terrestrial wildlife species (Naiman et al., 1993) and a high diversity of avian species (Cartron et al., 2000). In New Mexico, approximately 80% of all sensitive vertebrate species use **riparian habitats** during some time of their life history (NMDGF, 2006).

Early human inhabitants often settled adjacent to a riparian area and used it for shelter, food, and recreation. They understood that the natural systems were providing **ecosystem services**, defined as the goods and services from ecological systems that benefit people. Indigenous peoples implemented agricultural practices adapted to the local climate using sustainable crops and appropriate water harvesting strategies from these riparian areas (Dunmire, 2004). Starting with the Spanish colonization in the late 16th century, an irrigation network of **acequias**—gravity-fed irrigation canals and ditches that were usually unlined—expanded across the arid Southwest. To this day, the remaining acequias are managed by the community that surrounds them and have withstood major political changes (Rivera,

1998). Traditional knowledge regarding the management of these resources is passed through generations and remains an important component of community structure (Folke et al., 2003). As we will discuss later in this chapter, acequias mirror natural hydrological and ecological functions and aid in the maintenance of ecosystem services (Fernald et al., 2007).

Today, human population growth and urbanization represent major threats to acequias (Cox and Ross, 2011). Other threats include poor land management, floods, and wildfires (De Grenade Krueger et al., 2014). In acequia systems that have persevered, communities have shifted land use from growing fruit trees and row crops to increasing residential development (Ortiz et al., 2007). Nonetheless, acequias have persisted for long periods of time due to the inherent adaptability of the community to external threats (Fernald et al., 2012). These communities have traditionally relied not only on knowledge about climatic conditions, crops, soil, and plant water requirements (Glick, 2006) but also on a tradition of partitioning the water equally to meet the requirements of the acequia users even when water is limited (Fernald et al., 2012). As discussed in “Perceptions of Drought Preparedness and Adaptation Strategies within Acequia Communities,” acequia communities exhibit high adaptability and have shown an interest in understanding and utilizing new technologies to manage the effects of climate change (Fernald et al., 2012; Mayagoitia et al., 2012). Thus, the structure of acequias and the culture of the community that surrounds them are the strengths against emerging climatic effects such as water shortages (Mayagoitia et al., 2012).

### Biotic communities of acequias

Traditional acequia irrigation systems function in resemblance to naturally occurring riparian settings and represent an important transition zone between aquatic and upland environments (Fernald et al., 2007). In Northern New Mexico, acequias are located near high-elevation snow fields, have no storage systems, and divert water from snowmelt runoff into the irrigated fields (Phillips et al., 2015; Rango et al., 2014).

These acequia-irrigated systems also support grazing, firewood, timber, recreation, and hunting. Livestock and wildlife use riparian habitat and pastures as corridors when species move into **upland habitat** (Eastman and Gray,



1987). Forage provided by acequias is an important driver in livestock herd dynamics and a factor in local ranching and farming (López, 2014).

Across the world, abandonment of traditional irrigation practices has resulted in sediment deposition in areas that previously supported wildlife such as amphibians (Regalado, 1999). Also, as a result of fluctuations in water flow, changes in vegetation have caused the decline of the common frog (*Rana temporaria*) (Oteiza, 1998). Similarly, the destruction of acequias to build roadways has threatened the Spanish pond turtle (*Mauremys leprosa*) and the European pond turtle (*Emys orbicularis*) (Gómez-Cantarino and Lizana, 2000). In some cases, urban acequias, ditches, and canals sustained a similar richness of frogs and toads as in nearby natural environments; a multitude of amphibians used the irrigated areas as biological corridors (Acosta et al., 2005). However, an invasive species, the American bullfrog (*Lithobates catesbeianus*), has colonized new areas using acequias, canals, and ditches as corridors in Ciudad Juárez, Janos, and Ascención in northern Mexico, affecting local wildlife (Lavin et al., 2014).

The loss of traditional agricultural systems also threatens the diversity of crops. In general, acequia-irrigated fields have high agricultural diversity, and sometimes very unique cultivars and heritage species are preserved (De Grenade and Nabhan, 2013; Nabhan et al., 2010). For example, in the Baja California peninsula, the Jesuits established acequias, which are dependent on springs and channels (Cariño et al., 2013; De Grenade and Nabhan, 2013). Currently, these acequias continue supporting gardens and cultivated terraces with diverse vegetation; usually date palms are found in the upper story, fruit trees in the middle, and vegetables covering the lower story (Cariño et al., 2013; De Grenade and Nabhan, 2013). Here, field gardens are considered refuges for agrobiodiversity as some old isolated trees have genes that have been disappearing, such as limón real and naranja lima (De Grenade et al., 2014).

## Ecosystem services

Ecosystems function through various processes (e.g., photosynthesis, decomposition, food webs). In turn, humans depend on certain goods and services from these processes. Humans are, however, continually altering the landscape, and in some cases, this leads to biodiversity degradation and loss of **ecosystem integrity** (McKee et al., 2004). In the past, management of wildlife often focused on individual species (e.g., game species or Threatened and Endangered Species) and their habitats. Recently, ecologists have begun to focus on ecosystem services (Tilman, 2000; Reid et al., 2005; Naidoo et al., 2008; Boykin et al., 2013). The ecosystem services concept suggests that conservation efforts should focus on ecosystems and landscapes instead of individual species to preserve biodiversity and ensure the availability of these goods and services to humans (Franklin, 1993; Levin, 1998; Braat and de Groot, 2012).

For example, an important service of dense riparian vegetation is the sequestration of contaminants (e.g., pesticides and fertilizers) as they are translocated from upland environments into riparian zones (Lowrance et al., 1985). Furthermore, dense riparian vegetation and its dense root systems aid in holding sediments and supporting streambanks during normal and high flow events (Beschta and Platts, 1986). Dense riparian vegetation also plays a critical role in the containment of sediments with a rich profile of nutrients that promote growth and development, as well as **turbidity** mitigation of aquatic habitats, and it may reduce the risk of **eutrophication** (Meehan and Platts, 1978).

The loss of ecosystem services can potentially place human well-being at risk from loss of surface water, water flow regulation, and soil retention, among others, affecting food production and availability of potable water for human consumption (Reid et al., 2005; Egoh et al., 2009). Currently, this risk is not completely understood as researchers try to grasp the full extent of these ecosystem services and the link to biodiversity. However, some studies suggest that high levels of biodiversity are linked to ecosystem functioning, and thus the production of ecosystem services (Yachi and Loreau, 1999; Balvanera et al., 2006; Braat and de Groot, 2012). As time goes on, we continue to lose ecosystem services because of the increased ecosystem alteration in response to human demands and increasing populations (Hutton and Leader-Williams, 2003; Reid et al., 2005).

In order to ensure that biodiversity and ecosystem services are preserved for the future, there is a need to understand how growing human populations and land use change will affect biodiversity in the southwestern United States. Population growth and land use change (such as human development and conversion to agriculture) are some of the impacts considered to be of greatest concern (Sala et al., 2000; Mattison and Norris, 2005; Swetnam et al., 2011). The U.S. Census Bureau reported the United States population grew 13.2% from 1990 (249 million) to 2010 (308 million). The population is projected to be 363,584,435 in 2030, a 29.2% increase from 2000 (U.S. Census Bureau, 2018). The Southwest is one of the fastest growing regions in the United States, and New Mexico's population is expected to grow from 1.8 million in 2000 to 2.1 million in 2030 (U.S. Census Bureau, 2005). This increase in projected population will increase pressure placed on natural lands, resources, and wildlife.

In addition, previous studies highlighted a need for continuing research on the effect of land use change on ecosystem services, biodiversity, and wildlife habitat (Braat and de Groot, 2012; Boykin et al., 2013). For example, endangered species' habitats have decreased directly due to housing development (Liu et al., 1999). The link wildlife shares with ecosystem services is a topic of several studies (Braat and de Groot, 2012; Boykin et al., 2013).



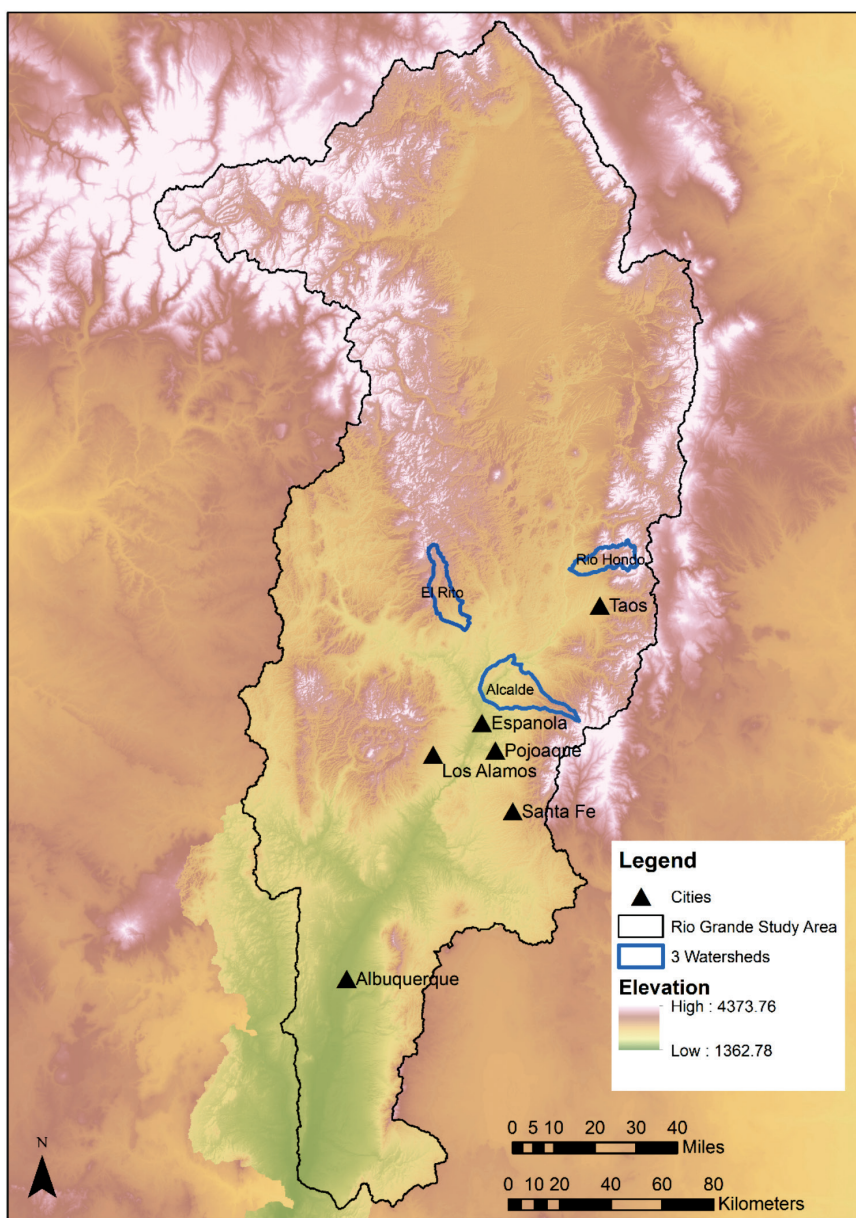
## Hydro-ecosystem services

Traditional irrigation systems, such as acequias, provide multiple **hydro-logic services** like recharging aquifers (Fernald et al., 2015), providing return flow to streams (Konrad et al., 2005; Ochoa et al., 2013a), and supporting riparian vegetation (Dahm et al., 2002; DeBano and Schmidt, 1989). **Seepages** from acequias resemble natural hydrologic services and define the presence of riparian vegetation (Fernald and Guldán, 2004). Beneficial seepage originates from unlined ditches, while concrete-lined canals have a reduced ability to recharge groundwater (Calleros, 1991; Drost et al., 1997). Field studies in reaches of the upper Española Valley have found that approximately 5–16% of the total water seeps out of the banks of acequias and into shallow water aquifers during the growing season (Fernald and Guldán, 2006; Fernald et al., 2007).

Seepage can also play a role in the dilution of agrochemicals and leachate from septic tanks in acequia-irrigated communities (Fernald and Guldán, 2006). The process of diluting chemicals facilitated by acequia seepage also protects deeper aquifers from toxicant accumulation by translocating contaminants (Fernald et al., 2007). Studies have found that seepage from unlined ditches diluted the ion concentration in nearby groundwater aquifers while the water was flowing during the irrigation season and reported that ions accumulated when it was not flowing (Helmus et al., 2009). In other cases, reduction in seepage resulted in limited groundwater recharge and salinization of different areas in the irrigation canal (Singh et al., 2006) and higher groundwater nitrate concentrations (Drost et al., 1997). Others have reported that agricultural landscapes can exchange groundwater at a rate that removes nitrate from surface and groundwater (Sjodin et al., 1997). In California, groundwater recharge by irrigation seepage contributes greatly to the amount available of water and, more importantly, to the quality of groundwater (Schmidt and Sherman, 1987). Therefore, riparian and hydrologic functions are supported by seepage from acequias and acequia-irrigated fields in the form

of **aquifer recharge** and return flow to rivers and streams, thus supporting most of the biodiversity of arid regions (Fernald et al., 2015).

Additional studies have shown that about 60% of the diverted water has been reported to recharge the river in the form of surface flow (Fernald et al., 2010). Although **evapotranspiration** from riparian vegetation results in a major withdrawal of groundwater in arid ecosystems (Dahm et al., 2002), it also affects water flow fluctuations (Nyholm et al., 2003; Winter et al., 1998) because dense riparian vegetation slows down flood water, allowing for infiltration and aquifer recharge (DeBano and Schmidt, 1989).



**Figure 1.** Map of the study area, the Upper Rio Grande River Basin, beginning with the headwaters in Colorado and flowing south into New Mexico.

## Current work

Human induced changes to biodiversity, including related species population declines, have occurred more rapidly in the past 50 years than at any other time in history. The forces driving such changes are steady, showing no evidence of decline over time, or are increasing in intensity (Reid et al., 2005). Global population growth highlights the need to understand the relationship between change in land use, biodiversity, and ecosystem services (Mattison and Norris, 2005; Crossman et al., 2013).

A way to study the effects of future change on ecosystems and species is using **alternative futures**. With alternative futures, multiple scenarios are created based on differing decisions and outcomes (climate and development scenarios) to provide decision makers with perspectives based on those different potential outcomes. We can use these alternative futures to evaluate the effect of different policies and management actions on biodiversity and ecosystem services (Steinitz et al., 2003). As elaborated in the *Datasets* section of this chapter, the United States Environmental Protection Agency (USEPA) created alternative futures scenarios with their Integrated Climate and Land-Use Scenarios (ICLUS) dataset that can be used to study the future impacts of population growth and urban development (Bierwagen et al., 2010). The ICLUS dataset identifies five potential scenarios of population growth and housing development from 2000 to 2100 based on Intergovernmental Panel on Climate Change (IPCC) scenarios (Bierwagen et al., 2010).

Population growth, urbanization, and shifts away from traditional land use practices threaten watersheds across the southwestern United States (Steinitz et al., 2003; Fernald et al., 2007). Our goal in studying alternative futures was to address questions connected to the relationship of population growth and urbanization and the future of acequia systems, biodiversity, and wildlife habitat. Our baseline study focused on **species rich areas** (areas where more species were predicted to occur) within the larger watershed and identified areas that provide ecosystem services related to biological conservation. We investigated the effect of future land use on species habitat in a watershed in the American Southwest. We compared future land use scenarios in the Upper Rio Grande River Basin using the USEPA ICLUS dataset to measure future urban grow-out effects on four biodiversity metrics (Boykin et al., 2013) derived from the Southwest Regional Gap Analysis Project (SWReGAP) habitat models (Boykin et al., 2007). Our effort quantifies the area and magnitude of the changes depending on the future scenarios to test the hypothesis that traditional acequia systems in Northern New Mexico provide resiliency and sustainability to ecosystems.

## METHODS

### Study area

The study area was the Upper Rio Grande River Basin (Figure 1), which includes the cities of Albuquerque, Rio Rancho, and Santa Fe as well as the Rio Chama. This watershed is projected to be among the top 40 fastest growing regions in the United States by 2030 (U.S. Census Bureau, 2005). The study area stretched from the Rio Grande headwaters in Colorado south to the confluence with the Rio Puerco south of Albuquerque, NM and encompassed an area of approximately 19,500 square miles (50,378 km<sup>2</sup>). Elevations ranged from 4,500 ft to over 14,000 ft (1,400 m to 4,350 m) above sea level, with precipitation increasing with elevation (Bartolino and Cole, 2002). Major vegetation types included piñon-juniper woodlands, ponderosa pine woodlands, semi-desert shrub steppe, and semi-desert grasslands (Lowry et al., 2007).

### Datasets

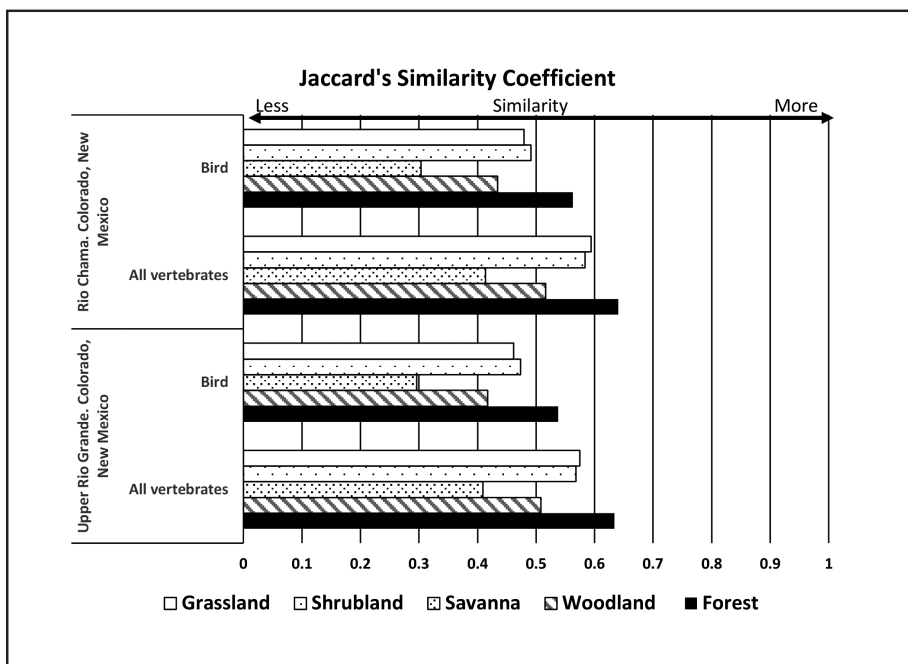
The United States Geological Survey (USGS) developed regional datasets, like SWReGAP, focusing on biodiversity conservation through the Gap Analysis Program (GAP) (Prior-Magee et al., 2007). GAP used land cover data derived from remote sensing and other environmental factors, such as landforms and elevation, to predict suitable habitat for 817 terrestrial vertebrates (amphibians, birds, mammals, and reptiles) throughout the U.S. Southwest states of Arizona, Colorado, Nevada, New Mexico, and Utah (Boykin et al., 2007; Prior-Magee et al., 2007). Another GAP dataset is the protected areas database that identifies land ownership and long-term biodiversity management. The data were available at pixel level or about 99 ft by 99 ft (30 m by 30 m).

The USEPA's Office of Research and Development created the ICLUS dataset (Version 1.3.1) to identify potential scenarios of population growth and housing development from 2000 to 2100 (USEPA, 2009; Bierwagen et al., 2010). This seamless, national-scale spatial dataset allows for analysis of projections of housing density on a decadal basis for five future climate scenarios, including a U.S. Census baseline condition (BC) and four modified scenarios (A1, A2, B1, and B2). These scenarios have different underlying assumptions consistent with the IPCC global greenhouse gas emission storylines (Table 1) (Bierwagen et al., 2010). The data exist as 13 different classified land cover types based on housing densities. ICLUS data have a baseline date of 2000.

### Analysis

We analyzed the habitat of all species modeled to understand which species were associated with riparian areas as well as grasslands, savannas, shrublands, woodlands, and forests. This provided us an estimate of combined use and connection between these various vegetation types.

Table 1. Description of the Five ICLUS Scenarios (U.S. Environmental Protection Agency, 2009)	
Scenario	Description
Baseline condition (BC)	Represents a level of medium fertility rates, medium domestic migration, and medium international migration.
A1	Represents fast economic growth, low population growth, and high global integration. Fertility is low, with high domestic and international migration.
B1	Represents a globally integrated world but with more emphasis on environmentally sustainable economic development. Fertility and domestic migration are low while international migration is high.
A2	Represents continued economic development with more regional focus and slower economic convergence between regions. Fertility and domestic migration are high and international migration is medium.
B2	Represents a regionally oriented world of moderate population growth and local solutions to environmental and economic issues. Fertility rates are medium, with low domestic migration and medium international migration.



**Figure 2. Jaccard's Similarity Coefficients for comparison between upland habitats (grassland, shrubland, savanna, woodland, forest) and riparian habitat within the watersheds (Upper Rio Grande: Colorado, New Mexico; Rio Chama: Colorado, New Mexico).**

We used Jaccard's Similarity Coefficient for this measure, which compared the species associated with each individual habitat and found in common with the other habitats.

Boykin et al. (2013) used **biodiversity metrics** to analyze factors of biodiversity. Biodiversity metrics are species richness datasets based on species habitat models that reflect a portion of biodiversity or some type of ecosystem service. We derived four biodiversity metrics from 817 terrestrial vertebrate habitat models developed by SWReGAP (Boykin et al., 2007, 2010, 2013). The four metrics we used were 1) vertebrate species richness, 2) bird species richness, 3) number of harvestable species, and 4) number of

Threatened and Endangered Species (T&E).

Vertebrate species richness is a summation of all the terrestrial species that could occur in each pixel of the selected watershed out of 817 species that were modeled throughout the U.S. Southwest (Boykin et al., 2013). Vertebrate species richness represents a surrogate for all biodiversity and includes amphibians, birds, mammals, and reptiles. Bird species richness is a summation of all bird species that could occur in each pixel and indicates the value the birding community has placed on areas with a large number of bird species for cultural and aesthetic reasons (Wenny et al., 2011). Bird richness represents an economic value in terms of birding-associated tourism, insect pest control, or seed dispersal (Wenny et al., 2011). Number of harvestable species is the number species listed by state wildlife

agencies to be of consumptive use through hunting, trapping, or other harvesting. Harvestable species not only provide food for hunters but can provide recreational value for hunters and non-hunters alike. Hunting can also stimulate local economies through guide fees, outfitting, tourism, and other expenditures. Number of T&E is the number of species listed by the federal government under the Endangered Species Act. T&E are valued by society and given legal priority in management.

We then extracted ICLUS data for the regional study area and reclassified to urban and nonurban areas. The ICLUS dataset identified 13 land cover classifications that



**Table 2. Area [mi<sup>2</sup> (km<sup>2</sup>)] Change for Land Cover Types from 2000–2100 for the Upper Rio Grande River Basin by ICLUS Scenarios (U.S. Environmental Protection Agency, 2009)**

Land cover	Scenarios				
	A1	A2	B1	B2	BC
Exurban	1,553 (4,022)	416 (1,078)	317 (820)	339 (878)	146 (377)
Suburban	1,933 (5,007)	7,090 (18,364)	106 (274)	270 (700)	129 (333)
Urban	73 (188)	37 (95)	1 (3)	2 (6)	1 (3)
Natural areas	-3,559 (-9,217)	-7,543 (-19,537)	-424 (-1,097)	-611 (-1,583)	-275 (-712)
Percent loss of natural areas	-1.65%	-3.49%	-0.20%	-0.28%	-0.13%

were aggregated into four classifications based on acres per housing unit (ac/housing unit): urban (<0.25 ac/housing unit), suburban (0.25–2 ac/housing unit), and exurban (2–40 ac/housing unit), while areas with more than 40 ac/housing unit were considered rural or natural areas (USEPA, 2009). We then calculated the amount of natural area that was projected to be lost as part of the urban grow-out. Next, we overlaid the baseline condition (year 2000) on each biodiversity metric to compare to the worst-case scenario (A2) in 2100 using geographic information systems (GIS) software (ESRI ArcInfo 10.0). We used Jaccard's Similarity Coefficient to identify similarity between riparian areas and upland habitat types. Jaccard's Similarity Coefficient provides values between 0 and 1, with values nearer 1 indicating high similarity and values close to 0 indicating little similarity.

## RESULTS

### Species connectivity

Analysis of habitat association for all vertebrates and just for birds identified a pattern of similarity between forests and riparian areas (Figure 2). Within the two larger watersheds that make up the study area (Upper Rio Grande: Colorado, New Mexico; Rio Chama: Colorado, New Mexico), the forest-riparian comparison identified the highest Similarity Coefficients. More terrestrial vertebrate species use the combination of riparian areas and forest than a combination of riparian areas and grasslands, savannas, shrublands, or woodlands.

In the Southwest, riparian habitats provide sources of water, unique structure, and refugia for species in drier ecosystems. Overall, our analysis of the habitat models suggests a higher number of species are associated with both riparian and forest habitats.

### Natural areas

The amount of natural area converted to the three categories of urban areas (exurban, suburban, and urban) was calculated for each of the five ICLUS scenarios (Table 2). The A2 scenario had the greatest change, with a loss of 7,543 square miles (19,537 km<sup>2</sup>) (3.49%) of natural areas

(Table 2). The A1 scenario had less than half the loss of A2, and the other three scenarios (B1, B2, and BC) had losses of less than 0.28%.

### Species richness

Areas with the highest and lowest species richness occupy a relatively small proportion of the study area, while the majority of areas have moderate species richness. Spatial depictions of these richness layers provide additional insight as to the location of these richness areas (Figures 3 and 4). In all figures, the species richness ranges from green (low number of species) to red (high number of species). Study areas are shown as blue polygons and urban areas are indicated as black. In all cases, we identified riparian habitats as species rich areas. As previously mentioned, these areas are focal areas in drier landscapes.

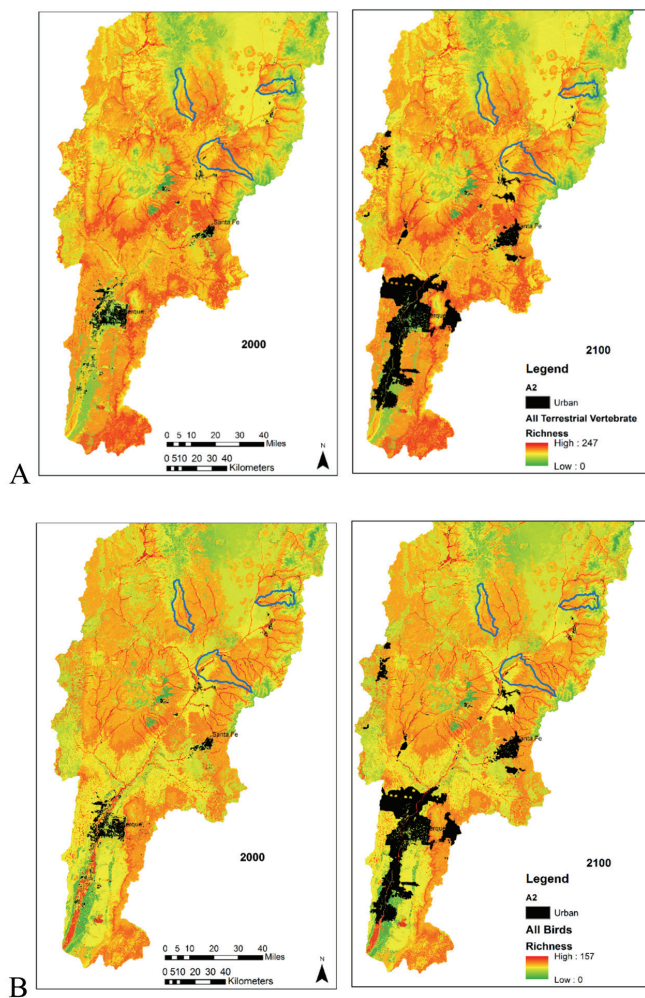
The areas with the lowest total species richness are in the high mountains and in the larger valleys with broader scale agriculture. The riparian areas are areas of higher richness, as are the woodland uplands. These woodlands serve as habitat for lower elevation savanna species as well as higher forest species.

For birds, the majority of habitat is in the moderate to moderately high richness range. Bird species rich riparian areas are more pronounced than with all terrestrial vertebrates. Woodland areas are moderately species rich, with the lower valley woodlands having fewer species. Again, this reflects woodlands providing species habitats for lower and higher elevation species.

Harvestable species analysis indicated similar patterns as birds and all-terrestrial vertebrate metrics, with riparian habitats as the more species rich and woodlands and lower forest as moderately rich. The lower valleys are more species rich than with the all-terrestrial species and bird species metrics, with the exception of the area south of Albuquerque.

For T&E richness, riparian habitats provide habitat for more species. There are other areas that are species rich as well, including areas south of Santa Fe and in the lower elevation in the upper watershed (San Luis Valley). The



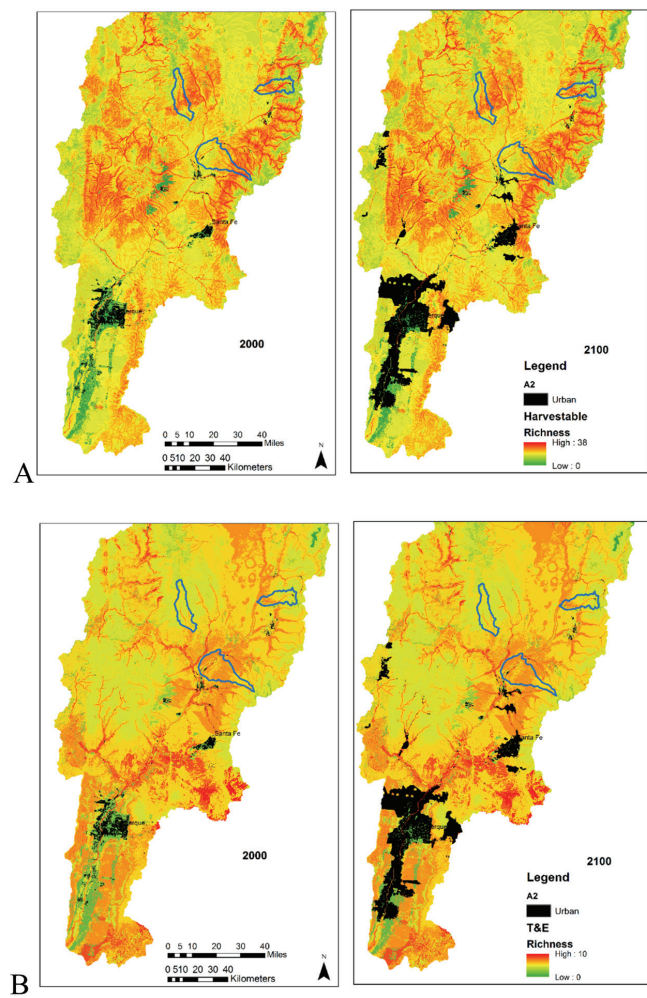


**Figure 3.** Maps of the Upper Rio Grande River Basin depicting species richness and urban growth. A) All terrestrial vertebrate species richness (number of species) and B) all bird species richness within the upper Rio Grande watershed in New Mexico. The three small watersheds that were the focus of fine-scaled research are outlined in blue.

area south of Albuquerque remains a less species rich area than most other areas.

### Growth effect on species richness

The urban growth provided within the subsequent figures is based on the A2 scenario, which displays the most expected growth by 2100. In these figures, species richness did not change between timeframes. The analysis at this broad scale did not identify a large change within the finer scaled watersheds of Alcalde, El Rito, and Rio Hondo. The majority of urban growth is associated with Albuquerque and Santa Fe and to a lesser extent Española and Pojoaque. More habitat loss occurred for the all-terrestrial vertebrate species richness metric in the areas with a



**Figure 4.** Maps of the Upper Rio Grande River Basin depicting species richness and urban growth. A) All harvestable species richness (number of species) and B) federally listed T&E terrestrial vertebrate species richness within the Upper Rio Grande watershed in New Mexico. The three small watersheds that were the focus of fine-scaled research are outlined in blue.

moderate number of species (Figure 3A). The most species rich areas are predicted to lose about 5% of habitat (Figure 3A). For birds, the majority of habitat loss was in areas with a moderate number of species, though larger percentages (greater than 10%) are predicted to be lost in areas with high species numbers (Figure 3B). Harvestable species analysis showed that the majority of habitat loss was in areas with a low to moderate number of species (Figure 4A). There was a loss of greater than 5% in the lowest richness areas (Figure 4A). Urban conversion increased to almost 7% of the lowest richness areas. For T&E richness, areas with moderate to low richness were affected the most in scenario A2 (Figure 4B).

## DISCUSSION

Our analysis identified several important points from a regional perspective. First, riparian areas are the most species rich areas within the Northern Rio Grande watershed. This perspective reaffirms recent field work conducted in riparian areas in the U.S. Southwest (Thompson et al., 2002; Skagen et al., 2005; NMDGF, 2006; Arizona Game and Fish Department, 2012; Ochoa et al., 2013b). More species use both riparian areas and forested habitat than any other riparian-land cover type combination. Another important conclusion is that these are the areas that are at the most risk from land use changes associated with climate change based on the USEPA ICLUS data. Villarreal et al. (2013) found similar results in the Santa Cruz watershed of Arizona and Sonora, Mexico.

We focused on scenario A2, which has the most human development for all scenarios, but all climate and land use change scenarios identified a loss in natural areas and habitats. All four biodiversity metrics (all vertebrate species, bird species, harvestable species, and T&E) were affected. Scenario A2 represents a future where population is growing more rapidly than other scenarios, and economic development is region-dependent (USEPA, 2009). Areas that were species rich for all terrestrial vertebrate species and bird species experienced decreases, with the largest decline occurring for bird species richness. The richest area for these species occurs within riparian areas adjacent to the river and tributaries where urban development is occurring most rapidly (NMDGF, 2006). In the northern portion of the Rio Grande, primarily in the mountainous regions, the land is under federal management, but much of the riparian and lowland areas are not (Prior-Magee et al., 2007).

New Mexico was projected to grow 15.4% between 2000 and 2030, with medium migration occurring, which is consistent with scenario BC (U.S. Census Bureau, 2005; Bierwagen et al., 2010). New Mexico's population grew 15.2% between 2000 and 2018 (U.S. Census Bureau, 2018). The Rio Grande Basin has large urban cities (e.g., Albuquerque and Santa Fe) adjacent to the Rio Grande or along tributaries. Much of the expected growth or disturbance will be associated with these areas. However, outlying communities will also be expanded into, and this includes areas with acequias. Thus, the outcome of this analysis is related to the management and resiliency of acequias in Northern New Mexico since these traditional irrigation communities provide an ecosystem service by extending the water flow and soil moisture to further support additional riparian habitat (Fernald et al., 2007). Furthermore, our analysis supports the hypothesis of the larger National Science Foundation (NSF) **Dynamics of Coupled Natural and Human Systems Program** (Coupled Natural and Human Systems or CNH) (Fernald et al., 2012) that traditional acequia systems in Northern New Mexico provide resiliency and sustainability for the communities.

As stated before, acequias duplicate natural hydrological and ecological functions and aid in the maintenance of ecosystem services. Management supporting the continued use of acequias and the extension and maintenance of riparian habitat along these water systems is important. Loss of these habitats not only impacts species that solely use riparian areas but will also affect those species that use the rest of the watershed. A reduction in the quality and quantity of habitat within the study area has the potential to be a tipping point for the sustainability of these systems. However, additional research is needed on the relationship between acequia systems, biodiversity, and wildlife habitat (Fernald et al., 2012).

Alternative futures studies such as this are useful tools in evaluating the effect of different policies, management regimes, and scenarios on biodiversity (Steinitz et al., 2003). Few projects have focused on similar questions at these broad scales (Steinitz et al., 2003; Samson et al., 2011, 2018). Additional studies are needed to look at these scales across varying geographies, at finer scales, and under different future scenarios (Mattison and Norris, 2005; Villarreal et al., 2013).

## KEY RESEARCH NEEDS

This analysis was based on species habitat models and urban growth scenarios. We did not include environmental factors associated with urban growth (e.g., water contaminants, air contaminants, or invasive species). Other direct and indirect impacts of urban growth can also increase habitat loss. We derived metrics from modeled habitat based on a land cover dataset circa 2000 (Lowry et al., 2007; Boykin et al., 2007). The species habitat models do not include changes in vegetation between 2000 and 2100 because future land cover types at the scale used are not available. Thus, we compared future climate and land use scenarios through time to the same baseline habitat data. Vegetation changes due to climate change will likely exacerbate results observed here. There are additional environmental stressor variables, such as fire, flooding, or drought, that can also affect change in land cover.

As with all modeling endeavors, an adaptive management framework should be put into place. Adaptive management provides a method to test current model output and obtain data to modify the output as knowledge is gained.

## CONCLUSIONS

This research provides an example of a large-scale investigation of future urban growth and its impact on a watershed in the U.S. Southwest. The analysis can inform managers and policy makers on potential patterns of growth and the resultant impact on biodiversity and ecosystem services. The analysis identifies areas of conservation need and can assist in policies and management that proactively conserve biodiversity instead of retroactively protecting what remains. The analysis also identifies areas for further research

within the Coupled Natural and Human Systems that make up the current study area. The most species rich areas within this study are the riparian habitats adjacent to the rivers and tributaries within the watershed. These same areas are associated with acequia systems. Focused conservation along the river and associated riparian vegetation in areas of high biodiversity should help mitigate direct impacts of urbanization, and acequias can play a significant role.

## ACKNOWLEDGMENTS

We thank William Kepner, David Bradford, Anne Neale, Kevin Gergely, and Alexa McKerrow for input into the creation of biodiversity metrics. We thank Rachel Guy, Allison Leimer, Darin Kopp, and Forrest East for assembling the biodiversity metrics for this project. This study was funded in part by the New Mexico Agricultural Experiment Station and the National Science Foundation grant #1010516 Dynamics of Coupled Natural and Human Systems Program. Additional financial assistance was provided by the USGS, New Mexico Cooperative Fish and Wildlife Research Unit, and the New Mexico State University Agricultural Experiment Station.

## REFERENCES

- Acosta, R., R.V. Mesones, and A. Núñez. 2005. Fauna de anuros en la ciudad de Salta, Argentina. *Revista de biología tropical*, 53, 569–575.
- Arizona Game and Fish Department. 2012. Arizona's state wildlife action plan: 2012–2022. Phoenix: Arizona Game and Fish Department. Retrieved September 3, 2017, from <https://www.azgfd.com/wildlife/actionplan/>
- Aycrigg, J., G. Beauvais, T. Gotthardt, K. Boykin, S. Williams, S. Lennartz, K.T. Vierling, S. Martinuzzi, and L.A. Vierling. 2010. Mapping species ranges and distribution models across the United States. In *A geographic approach to planning for biological diversity*, USGS Gap Analysis Bulletin 18 (pp. 12–20). Moscow, ID: USGS.
- Balvanera, P., A.B. Pfisterer, N. Buchmann, J.S. He, T. Nakashizuka, D. Raffaelli, and B. Schmid. 2006. Quantifying the evidence for biodiversity effects on ecosystem functioning and services. *Ecology Letters*, 9, 1146–1156.
- Bartolino, J.R., and J.C. Cole. 2002. Ground-water resources of the middle Rio Grande basin, New Mexico [1222]. Reston, VA: U.S. Department of the Interior and U.S. Geological Survey.
- Beschta, R.L., and W.S. Platts. 1986. Morphological features of small streams: Significance and function. *Journal of the American Water Resources Association*, 22, 369–379.
- Bierwagen, B.G., D.M. Theobald, C.R. Pyke, A. Choate, P. Groth, J.V. Thomas, and P. Morefield. 2010. National housing and impervious surface scenarios for integrated climate impact assessments. *Proceedings of the National Academy of Sciences*, 107, 20887–20892.
- Boykin, K.G., B.C. Thompson, and S. Propeck-Gray. 2010. Accuracy of gap analysis habitat models in predicting physical features for wildlife-habitat associations in the Southwest United States. *Ecological Modelling*, 22, 2769–2775.
- Boykin, K.G., B.C. Thompson, R.A. Deitner, D. Schrupp, D. Bradford, L. O'Brien, ... and Z. Schwenke. 2007. Predicted animal habitat distributions and species richness. In J.S. Prior-Magee et al. (Eds.), *Southwest Regional Gap Analysis Final Report*. Moscow, ID: U.S. Geological Survey and Gap Analysis Program.
- Boykin, K.G., W.G. Kepner, D.F. Bradford, R.K. Guy, D.A. Kopp, A.K. Leimer, E.A. Samson, N. Forrest East, A.C. Neale, and K.J. Gergely. 2013. A national approach for mapping and quantifying habitat-based biodiversity metrics across multiple spatial scales. *Ecological Indicators*, 33, 139–147.
- Braat, L.C., and R. de Groot. 2012. The ecosystem services agenda: Bridging the worlds of natural science and economics, conservation and development, and public and private policy. *Ecosystem Services*, 1, 4–15.
- Calleros, J.R. 1991. The impact on Mexico of the lining of the All-American Canal. *National Resources Journal*, 31, 829.
- Cariño, M., A. Breceda, A. Ortega, and L. Castorena. 2013. *Evocando al edén: Conocimiento, valoración y problemática del oasis de Los Comondú*. Barcelona, Spain: Icaria Editorial.
- Cartron, J.L.E., S.H. Stoleson, P.L. Stoleson, and D.W. Shaw. 2000. Riparian areas. In R. Jemison and C. Raish (Eds.), *Livestock management in the American Southwest: Ecology, society and economics* (pp. 281–328). Amsterdam, The Netherlands: Elsevier.
- Cox, M., and J.M. Ross. 2011. Robustness and vulnerability of community irrigation systems: The case of the Taos valley acequias. *Journal of Environmental Economics and Management*, 61, 254–266.
- Crossman, N.D., B. Burkhard, S. Nedkov, L. Willemsen, K. Petz, I. Palomo, E.G. Drakou, B. Martín-Lopez, T. McPhearson, K. Boyanova, R. Alkemade, B. Egoh, M.B. Dunbar, and J. Maes. 2013. A blueprint for mapping and modelling ecosystem services. *Ecosystem Services*, 4, 4–14.
- Dahm, C.N., J.R. Cleverly, J.E.A. Coonrod, J.R. Thibault, D.E. McDonnell, and D.J. Gilroy. 2002. Evapotranspiration at the land/water interface in a semi-arid drainage basin. *Freshwater Biology*, 47, 831–843.



- De Grenade, R., and G.P. Nabhan. 2013. Agrobiodiversity in an oasis archipelago. *Journal of Ethnobiology*, 33, 203–236.
- De Grenade, R., R. Krueger, G.P. Nabhan, and M.C. Olvera. 2014. Mission and modern citrus species diversity of Baja California peninsula oases. *Economic Botany*, 68, 266–282.
- DeBano, L.F., and L.J. Schmidt. 1989. Improving southwestern riparian areas through watershed management [Gen. Tech. Rep. RM-182]. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.
- Drost, B.W., S.E. Cox, and K.M. Schurr. 1997. Changes in ground-water levels and ground-water budgets, from predevelopment to 1986, in parts of the Pasco Basin, Washington [Water-Resources Investigations Report 96-4086]. Tacoma, WA: U.S. Geological Survey.
- Dunmire, W.W. 2004. *Gardens of New Spain: How Mediterranean plants and foods changed America*, 1st ed. Austin: University of Texas Press.
- Eastman, C., and J.R. Gray. 1987. *Community grazing: Practice and potential in New Mexico*. Albuquerque: University of New Mexico.
- Egoh, B., B. Reyers, M. Rouget, M. Bode, and D.M. Richardson. 2009. Spatial congruence between biodiversity and ecosystem services in South Africa. *Biological Conservation*, 142, 553–562.
- Fernald, A.G., and S.J. Guldán. 2004. River, acequia and shallow groundwater interactions [Water Task Force Report 2]. Las Cruces: New Mexico State University.
- Fernald, A.G., and S.J. Guldán. 2006. Surface water–groundwater interactions between irrigation ditches, alluvial aquifers, and streams. *Reviews in Fisheries Science*, 14, 79–89.
- Fernald, A.G., T.T. Baker, and S.J. Guldán. 2007. Hydrologic, riparian, and agroecosystem functions of traditional acequia irrigation systems. *Journal of Sustainable Agriculture*, 30, 147–171.
- Fernald, A.G., S.Y. Cevik, C.G. Ochoa, V.C. Tidwell, J.P. King, and S.J. Guldán. 2010. River hydrograph retransmission functions of irrigated valley surface water–groundwater interactions. *Journal of Irrigation and Drainage Engineering*, 136, 823–835.
- Fernald, A., V. Tidwell, J. Rivera, S. Rodríguez, S. Guldán, C. Steele, C. Ochoa, B. Hurd, M. Ortiz, K. Boykin, and A. Cibils. 2012. Modeling sustainability of water, environment, livelihood, and culture in traditional irrigation communities and their linked watersheds. *Sustainability*, 4, 2998–3022.
- Fernald, A., S. Guldán, K. Boykin, A. Cibils, M. Gonzales, B. Hurd, S. Lopez, C. Ochoa, M. Ortiz, J. Rivera, S. Rodriguez, and C. Steele. 2015. Linked hydrologic and social systems that support resilience of traditional irrigation communities. *Hydrology and Earth System Sciences*, 19, 293–307.
- Folke, C., J. Colding, and F. Berkes. 2003. Synthesis: Building resilience and adaptive capacity in social-ecological systems. In F. Berkes, J. Colding, and C. Folke (Eds.), *Navigating social-ecological systems: Building resilience for complexity and change*. Cambridge, NY: Cambridge University Press.
- Franklin, J.F. 1993. Preserving biodiversity: Species, ecosystems, or landscapes? *Ecological Applications*, 3, 202–205.
- Glick, T.F. 2006. Historical status and cultural meaning of historic hydraulic landscapes: Oasis. Paper presented at First International Congress on Oasis and Sustainable Tourism, Elche, Spain, December 15, 2006.
- Gómez-Cantarino, A., and M. Lizana. 2000. Distribución y uso del hábitat de los galápagos (*Mauremys leprosa* y *Emys orbicularis*) en la provincia de Salamanca. *Boletín de la asociación herpetológica Española*, 11, 4–8.
- Helmus, A.M., A.G. Fernald, D.M. VanLeeuwen, L.B. Abbott, A.L. Ulery, and T.T. Baker. 2009. Surface water seepage effects on shallow ground-water quality along the Rio Grande in northern New Mexico. *Journal of the American Water Resources Association*, 45, 407–418.
- Hubbard, J.P. 1977. Importance of riparian ecosystems: Biotic considerations. In *Importance, preservation and management of riparian habitat: A symposium* [General Technical Report RM-43]. Tucson, AZ: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture.
- Hutton, J.M., and N. Leader-Williams. 2003. Sustainable use and incentive-driven conservation: Realigning human and conservation interests. *Oryx*, 37, 215–226.
- Konrad, C.P., B.W. Drost, and R.J. Wagner. 2005. Hydrogeology of the unconsolidated sediments, water quality, and ground-water/surface-water exchanges in the Methow River Basin, Okanogan County, Washington [Water-resources investigations report 03-4244]. Okanogan County, WA: U.S. Department of the Interior, U.S. Geological Survey.
- Lavin, P.A., D. Lazcano, and H. Gadsden. 2014. Anfíbios y reptiles exóticos y trasladados invasores. *Especies acuáticas invasoras en México* (pp. 435–441). México: Comisión Nacional para el Conocimiento y Uso de la Biodiversidad.
- Levin, S.A. 1998. Ecosystems and the biosphere as complex adaptive systems. *Ecosystems*, 1, 431–436.
- Liu, J., Z. Ouyang, W.W. Taylor, R. Groop, Y. Tan, and H. Zhang. 2001. A framework for evaluating the effects of human factors on wildlife habitat: The case of giant pandas. *Conservation Biology*, 13, 1360–1370.
- López, S.C. 2014. *The role of livestock in suppressing rangeland weeds and sustaining traditional agropastoral communities in northern New Mexico* [doctoral dissertation]. Retrieved from WorldCat.org. (883916484).



- Lowrance, R., R. Leonard, and J. Sheridan. 1985. Managing riparian ecosystems to control nonpoint pollution. *Journal of Soil and Water Conservation*, 40, 87–91.
- Lowry, J., R.D. Ramsey, K. Thomas, D. Schrupp, T. Sajwaj, J. Kirby, ...and J. Prior-Magee. 2007. Mapping moderate-scale land-cover over very large geographic areas within a collaborative framework: A case study of the Southwest Regional Gap Analysis Project (SWReGAP). *Remote Sensing of Environment*, 108, 59–73.
- Mattison, E., and K. Norris. 2005. Bridging the gaps between agricultural policy, land-use and biodiversity. *Trends in Ecology and Evolution*, 20, 610–616.
- Mayagoitia, L., B. Hurd, J. Rivera, and S. Guldán. 2012. Rural community perspectives on preparedness and adaptation to climate-change and demographic pressure. *Journal of Contemporary Water Research and Education*, 147, 49–62.
- McKee, J.K., P.W. Sciulli, C.D. Foose, and T.A. Waite. 2004. Forecasting global biodiversity threats associated with human population growth. *Biological Conservation*, 115, 161–164.
- Meehan, W.R., and W.S. Platts. 1978. Livestock grazing and the aquatic environment: A thorough understanding of relationships between livestock grazing and fisheries is needed to manage range adjacent to coldwater streams. *Journal of Soil and Water Conservation*, 33, 274–278.
- Nabhan, G.P., J. Garcia, R. Routson, K. Routson, and M. Cariño-Olvera. 2010. Desert oases as genetic refugia of heritage crops: Persistence of forgotten fruits in the mission orchards of Baja California, Mexico. *International Journal of Biodiversity and Conservation*, 2, 56–69.
- Naidoo, R., A. Balmford, R. Costanza, B. Fisher, R.E. Green, B. Lehner, T.R. Malcolm, and T.H. Ricketts. 2008. Global mapping of ecosystem services and conservation priorities. *Proceedings of the National Academy of Sciences*, 105, 9495–9500.
- Naiman, R.J., H. Decamps, and M. Pollock. 1993. The role of riparian corridors in maintaining regional biodiversity. *Ecological Applications*, 3, 209–212.
- New Mexico Department of Game and Fish (NMDGF). 2006. *Comprehensive wildlife conservation strategy for New Mexico*. Santa Fe: New Mexico Department of Game and Fish.
- Nyholm, T., K. Rasmussen, and S. Christensen. 2003. Estimation of stream flow depletion and uncertainty from discharge measurements in a small alluvial stream. *Journal of Hydrology*, 274, 129–144.
- Ochoa, C.G., A.G. Fernald, S.J. Guldán, V.C. Tidwell, and M.K. Shukla. 2013a. Shallow aquifer recharge from irrigation in a semiarid agricultural valley in New Mexico. *Journal of Hydrologic Engineering*, 18, 1219–1230.
- Ochoa, C.G., S.J. Guldán, A.F. Cibils, S.C. Lopez, K.G. Boykin, V.C. Tidwell, and A.G. Fernald. 2013b. Hydrologic connectivity of head waters and floodplains in a semi-arid watershed. *Journal of Contemporary Water Research and Education*, 152, 69–78.
- Ortiz, M., C. Brown, A.S. Fernald, T.T.R. Baker, B. Creel, and S. Guldán. 2007. Land use change impacts on acequia water resources in northern New Mexico. *Journal of Contemporary Water Research and Education*, 137, 47–54.
- Oteiza, A.G. 1998. El declive de una población costera cantábrica de Rana bermeja (Rana temporaria). *Munibe ciencias naturales-Natur zientziak*, 50, 59–71.
- Phillips, F.M., G.E. Hall, and M.E. Black. 2015. *Reining in the Rio Grande: People, land, and water*. Albuquerque: University New Mexico Press.
- Primack, R.B. 2006. *Essentials of conservation biology*, 4th ed. Sunderland, MA: Sinauer Associates, Inc.
- Prior-Magee, J.S., K.G. Boykin, D.F. Bradford, W.G. Kepner, J.H. Lowry, D.L. Schrupp K. Thomas, and B.C. Thompson. 2007. Ecoregional gap analysis of the southwestern United States: *The Southwest Regional Gap Analysis Project final report*. Moscow, ID: U.S. Geological Survey, Gap Analysis Program.
- Rango, A., A. Fernald, C. Steele, B. Hurd, and C. Ochoa. 2014. Acequias and the effects of climate change. *Journal of Contemporary Water Research and Education*, 151, 84–94.
- Regalado, P.G. 1999. *Conservación de la herpetofauna gallega: Situación actual de los anfibios y reptiles de Galicia*. A Coruña, Spain: Universidade da Coruña, Servicio de Publicacións.
- Reid, W.V., H.A. Mooney, A. Cropper, D. Capistrano, S.R. Carpenter, K. Chopra, ...and M.B. Zurek. 2005. *Ecosystems and human well-being-synthesis: A report of the Millennium Ecosystem Assessment*. Washington, D.C.: Island Press.
- Rivera, J. 1998. *Acequia culture: Land, water, and community in the Southwest*. Albuquerque: University of New Mexico Press.
- Rodríguez, S. 2006. *Acequia: water sharing, sanctity, and place*. Santa Fe, NM: School for Advanced Research Press.
- Sala, O.E., F.S. Chapin, III, J.J. Armesto, E. Berlow, J. Bloomfield, R. Dirzo, ...and D.H. Wall. 2000. Global biodiversity scenarios for the year 2100. *Science*, 287, 1770–1774.
- Samson, E.A., K.G. Boykin, W.G. Kepner, M.C. Andersen, and A. Fernald. 2018. Evaluating biodiversity metric response to forecasted land use change in the Northern Rio Grande Basin. *Environments*, 5, 91.

- Samson, E.A., W.G. Kepner, K.G. Boykin, D.F. Bradford, B.G. Bierwagen, A.K.K. Leimer, and R.K. Guy. 2011. Evaluating biodiversity response to forecasted land use change: A case study in the South Platte River Basin, Colorado. In C.N. Medley, G. Patterson, and M.J. Parker (Eds.), *USGS status and trends report 2003: Fourth interagency conference on research in the watersheds* [USGS scientific investigations report 2011-5169]. Reston, VA: U.S. Geological Survey.
- Schmidt, K.D., and I. Sherman. 1987. Effect of irrigation on groundwater quality in California. *Journal of Irrigation and Drainage Engineering*, 113, 16–29.
- Singh, R., J.G. Kroes, J.C. van Dam, and R.A. Feddes. 2006. Distributed ecohydrological modelling to evaluate the performance of irrigation system in Sirsa district, India: I. Current water management and its productivity. *Journal of Hydrology*, 329, 692–713.
- Sjodin, A.L., W.M. Lewis, Jr., and J.F. Saunders, III. 1997. Denitrification as a component of the nitrogen budget for a large plains river. *Biogeochemistry*, 39, 327–342.
- Skagen, S.K., J.F. Kelly, C. van Riper, III, R.L. Hutto, D.M. Finch, D.J. Krueper, and C.P. Melcher. 2005. Geography of spring landbird migration through riparian habitats in southwestern North America. *The Condor*, 107, 212–227.
- Steinitz, C., H. Arias, S. Bassett, M. Flaxman, T. Goode, T. Maddock, III, D. Mouat, R. Peiser, and A. Shearer. 2003. *Alternative futures for changing landscapes: The upper San Pedro River Basin in Arizona and Sonora*. Washington, D.C.: Island Press.
- Swetnam, R.D., B. Fisher, B.P. Mbilinyi, P.K. Munishi, S. Willcock, T. Ricketts, S. Mwakalila, A. Balmford, N.D. Burgess, A.R. Marshall, and S.L. Lewis. 2011. Mapping socio-economic scenarios of land cover change: A GIS method to enable ecosystem service modelling. *Journal of Environmental Management*, 92, 563–574.
- Szaro, R.C. 1989. Riparian forest and scrubland community types of Arizona and New Mexico. *Desert Plants (USA)*, 9, 138.
- Thompson, B.C., P.L. Matusik-Rowan, and K.G. Boykin. 2002. Prioritizing conservation potential of arid-land montane natural springs and associated riparian areas. *Journal of Arid Environments*, 50, 527–547.
- Tilman, D. 2000. Causes, consequences and ethics of biodiversity. *Nature*, 405, 208–211.
- U.S. Census Bureau. 2005. 2005 Interim state population projections. Retrieved September 2, 2016, from <http://www.census.gov/population/projections/data/state/projectionsagesex.html>
- U.S. Census Bureau, Population Division. 2018. Annual estimates of the resident population for the United States, regions, states, and Puerto Rico: April 1, 2010 to July 1, 2018 [NST-EST2018-01]. Retrieved May 13, 2019, from <https://www.census.gov/newsroom/press-kits/2018/pop-estimates-national-state.html>
- U.S. Environmental Protection Agency (USEPA). 2009. Land-use scenarios: National-scale housing-density scenarios consistent with climate change storylines [EPA/600/R-08/076F, 2009]. Washington, D.C.: Office of Research and Development.
- Van Auker, O.W. 2009. Causes and consequences of woody plant encroachment into western North American grasslands. *Journal of Environmental Management*, 90, 2931–2942.
- Villarreal, M.L., L.M. Norman, K.G. Boykin, and C.S.A. Wallace. 2013. Biodiversity losses and conservation trade-offs: Assessing future urban growth scenarios for a North American trade corridor. *International Journal of Biodiversity Science, Ecosystem Services and Management*, 9, 90–103.
- Wenny, D.G., T.L. Devault, M.D. Johnson, D. Kelly, C.H. Sekercioglu, D.F. Tomback, and C.J. Whelan. 2011. The need to quantify ecosystem services provided by birds. *The Auk*, 128, 1–14.
- Winter, T.C., J.W. Harvey, O.L. Franke, and W.M. Alley. 1998. Ground water and surface water: A single resource [U.S. Geological Survey circular 1139]. Denver, CO: U.S. Geological Survey.
- Yachi, S., and M. Loreau. 1999. Biodiversity and ecosystem productivity in a fluctuating environment: The insurance hypothesis. *Proceedings of the National Academy of Sciences*, 96, 1463–1468.

# Surface Water and Groundwater Interactions in Acequia Systems of Northern New Mexico

Carlos G. Ochoa, Steve J. Guldan, and Sam Fernald

---

## INTRODUCTION

Irrigated agriculture uses a significant portion of fresh-water resources; in New Mexico, estimates range from 70–90% of usage. Given the increasing demands placed on limited water supplies, and uncertainty regarding future supplies, irrigated agriculture is facing increased scrutiny. For these reasons, there is a great need to improve our understanding of the hydrology of irrigated agriculture in the state. In north-central New Mexico, **acequias** are by far the predominant system by which cropland is irrigated. Each acequia consists of a main ditch or canal and usually a network of laterals. Acequias are for the most part earthen-lined and so they may exhibit **seepage conveyance losses**—slow movement of some of the water into the bed and banks of a canal, ditch, or acequia. Most irrigated fields typically employ flood or furrow irrigation that, depending on field soil type, has the potential to result in a significant amount of **deep percolation** (the total amount of water percolating below the root zone). Although many local irrigators and water managers have historically understood that this **seepage** can result in the rise of groundwater levels in shallow wells, limited quantitative data have been available for a detailed characterization of the hydrology of these systems. Overall, a more detailed understanding of water flow paths in the Rio Grande Basin has been needed, including diversions to and through acequia-irrigated agricultural systems—in particular the effects of seepage on aquifers and river flow.

The intent of this chapter is to provide an overview of research results and conclusions from hydrologic studies of acequia agriculture that took place in the region from 2001–2018.

Research questions related to acequia hydrology that we addressed included:

- 1) What is the amount and timing of acequia canal seepage recharge to shallow groundwater?
- 2) Is seepage from flood-irrigated fields a significant source of recharge to shallow groundwater?
- 3) What are the contributions of canal and field seepage to **groundwater return flow** and river flow?

## METHODS

### Study sites

In general, acequias in Northern New Mexico are located within relatively narrow valleys overlying shallow aquifers. That is the case for the three study sites (El Rito, Rio Hondo, and Alcalde) included in this report where we characterized surface water and groundwater interactions as influenced by acequia flow and irrigation. At these three study sites, spring snowmelt runoff highly determines the amount of river and acequia flow available for irrigation. River flow in turn is the main driver for ditch flow and irrigation water availability (Cruz et al., 2018). This is especially true for some acequias of El Rito where the irrigation season essentially ends when the snowmelt runoff that feeds the river and ditches ends. River flow typically peaks at the end of May or early June for the Alcalde and Rio Hondo sites and at the end of April or early May for the El Rito site.

At the Alcalde study site (5,700 ft elevation; 10 in. annual precipitation; extends approximately 12 miles along the reach between Alcalde and Velarde, NM), water for irrigation is diverted from the Rio Grande. The Rio Grande daily averaged streamflow ranged from 353 to 2,210 cubic feet per second (cfs) for the period of record 1930–2018 (United States Geological Survey [USGS], 2019). The Rio Grande and drainage from tributaries coming from the Sangre de Cristo Range on the east side of the basin influence regional groundwater flow at this site (Stephens D.B. and Associates, Inc., 2003). In the Alcalde-Velarde valley, the Rio Grande is considered a **gaining stream** (a stream that gains water from subsurface flows) (Helmus et al., 2009), and the slope of the water table is around 0.2% (Ochoa et al., 2009).

At the Rio Hondo study site (7,400 ft elevation; 12 in. annual precipitation), acequia farmers irrigate off of the Rio Hondo, which is a tributary to the Rio Grande. Daily average streamflow for the Rio Hondo ranged from 10 cfs (2002) to 384 cfs (1945) for the period of record 1934–2017 (USGS, 2019). At this study site, discharge from the Rio Hondo and its tributaries influences the groundwater flow. The Rio Hondo is considered a gaining stream above what is referred to as the Gates of Valdez, in the middle of the Rio Hondo Valley, and a **losing stream** (a stream that loses water into the

ground because the water table is below the bottom of the stream channel) below that point until reaching the Rio Grande (Johnson et al., 2009). Soil development within the upper portion of the watershed is limited depending on slope, aspect, and location (Frisbee et al., 2017).

At the El Rito study site (6,900 ft elevation; 12 in. annual precipitation), irrigation water is diverted from El Rito Creek, which is a tributary to the Rio Chama. El Rito Creek flow ranged from 1.8 to 142 cfs during the period of record 1931–1950 (USGS, 2019). Spring runoff largely influences river flow since most of the flow takes place during the snowmelt season that in most years occurs from March to June. At this study site, shallow groundwater flow is mainly driven by seepage contributions from irrigation (Gutierrez-Jurado et al., 2017) and the El Rito Creek. Some of the headwater springs that feed the El Rito Creek rely on underground flows coming from an adjacent basin (Canjilon) (Frisbee et al., 2016).

## Water budgets

**Water budgets** account for inputs and outputs of water in a defined region, such as a field, farm, valley, basin, or even an entire state. Important components of a water budget in an irrigated landscape include precipitation, canal/acequia flow, river flow, groundwater return flow, **evapotranspiration (ET)**, seepage, and **surface water return flows** (field and acequia tailwater that goes directly back to the river). Some of these water budget components can be considered **consumptive use**, or water that is lost from the system and no longer in a useable form. The most obvious case is evapotranspiration by which water is lost to the atmosphere from crop fields or riparian areas (water transpired by plants and direct evaporation from soil are together referred to as evapotranspiration). Other components of the budget may or may not constitute consumptive losses from the system, depending on the circumstances. For example, seepage out of irrigation ditches or below root zones in crop fields would be a consumptive use if the water reaches and mixes with highly saline groundwater where salt concentration in the water is too high for it to be pumped and used for human, livestock, or irrigation purposes without expensive treatment. On the other hand, if the seeped water reaches the shallow aquifer system or becomes subsurface return flow to a river or stream, then the water is not lost and remains as useable water in the system. The local community could then extract some of this water from local wells for household or small garden irrigation needs. Also, some of the groundwater return flow to the stream can become available for other human and environmental needs downstream.

## Field data collection

We instrumented study sites in order to monitor multiple water budget components, including soil moisture, irrigation, runoff, and weather. We also monitored shallow

groundwater level fluctuations at multiple locations in each study site. For detailed description of methods used in the various studies discussed in this chapter, please see Cruz et al. (2018), Cruz et al. (2019), Gutierrez-Jurado et al. (2017), Ochoa et al. (2013), Fernald et al. (2010), and Ochoa et al. (2007).

***Soil moisture.*** We used soil sensors to determine soil moisture content variability along the top approximately 1 m (3.3 ft) profile where most uptake of water by the plant occurs. For example, at the El Rito site, we installed sensors at 0.1, 0.4, 0.8, and 1 m (0.3, 1.3, 2.6, and 3.3 ft) depths (see for example Gutierrez-Jurado et al., 2017; Ochoa et al., 2013; and Ochoa et al., 2007).

***Irrigation water applied and runoff.*** We measured the amount of water applied for multiple irrigation events at each site. We used either an open channel flume (see for example Gutierrez-Jurado et al., 2017) or an in-line propeller flow meter to measure total irrigation application (see for example Ochoa et al., 2007). We also used open channel flumes for measuring tailwater running off the field at each site.

***Shallow groundwater level fluctuations.*** At each site, we used a number of monitoring wells for assessing shallow groundwater response to specific irrigation events and to monitor groundwater levels throughout the entire year. We installed multiple non-pumping monitoring wells (2 in. diameter) in various locations, mainly along the irrigated portion of the valleys. Also, we monitored multiple existing wells of community collaborators, including domestic wells, community wells, and other available wells. At the Alcalde site, we also used shallow groundwater level fluctuation data to estimate the recharge of the local aquifer at the field scale and at the valley scale.

***Irrigation contributions to deep percolation and aquifer recharge.*** We used data from several irrigation experiments conducted from 2005 through 2013 at the three different study sites in order to estimate groundwater recharge from irrigation percolation. Deep percolation can be variable depending on crop type. We conducted these irrigation experiments in fields, including alfalfa-grass, grass, oat-wheatgrass, and apple crops—all of which represent common crops in the region.

The **water balance method** is a way to create a water budget, and it has been successfully used for estimating deep percolation below the root zone (Ochoa et al., 2013). In many studies, deep percolation is often equated to **aquifer recharge** (Scanlon et al., 2002). The use of deep percolation as a surrogate to estimate groundwater recharge in shallow aquifers (e.g., <30 ft) is based on the premise that water that percolates below the root zone has the potential to reach the water table.

We used the soil water balance method for calculating deep percolation, which was equated to shallow aquifer recharge after different irrigation events in these crop fields. Because groundwater is relatively shallow (<15 ft)



in these crop fields, we assumed deep percolation can be directly equated to aquifer recharge. We used the following equation based on the water balance method to calculate deep percolation (DP) for several crop fields:

$$DP = P + I - RO \pm \Delta S - ET$$

Where,

$DP$  = deep percolation,

$P$  = precipitation,

$I$  = irrigation,

$RO$  = runoff,

$\Delta S$  = change in soil moisture, and

$ET$  = evapotranspiration.

Deep percolation ( $DP$ ), as described above, is the total amount of water percolating below the root zone, which can be variable depending on crop type. Irrigation ( $I$ ) and runoff ( $RO$ ) are estimated based on irrigation water entering and exiting the field. Change in soil moisture ( $\Delta S$ ) is calculated as the difference between soil moisture content at **field capacity** (amount of water the soil can hold when excess water has drained out) and soil moisture content prior to irrigation multiplied by the depth of the root zone, which was 2–3 ft in our studies. Evapotranspiration ( $ET$ ) is estimated based largely on weather data (for example, air temperature, solar radiation, and wind speed) collected onsite.

### Water budget estimates for the Alcalde study site

We used field-based measurements of surface water and groundwater to calculate a water budget for the Acequia de Alcalde. We calculated acequia water inflows and outflows and the amount of water used for irrigation, including amount of water applied, deep percolation, evapotranspiration, and field tailwater. We had three streamflow gauging stations, one upstream near the diversion, one mid-stream at the NMSU Alcalde Science Center, and one downstream near the end of the acequia. At the Alcalde Science Center, we conducted several field experiments to calculate the total amount of water used for irrigation. We used in-line propeller flow meters to measure the amount of water applied and flumes for estimating tailwater. We installed soil moisture stations for estimating deep percolation and calculated crop evapotranspiration based on data collected from an onsite weather station we installed. We extrapolated results from these irrigation experiments at the Alcalde Center to the entire valley scale (Fernald et al., 2010).

We used a field measurement approach to characterize the water balance of the area encompassed by the Acequia de Alcalde irrigation system. We used detailed measurements to account for all flow diverted from the river into

the Acequia de Alcalde irrigation canal. The Acequia de Alcalde water balance was formulated as follows:

$$\begin{aligned} &\text{Canal diversion} - \text{canal seepage} - \text{canal turnouts} \\ &- \text{canal return to river} = \text{crop evapotranspiration} \\ &\quad + \text{field tailwater} + \text{deep percolation} \end{aligned}$$

We calculated the amount of water being diverted for irrigation after subtracting canal seepage, turnouts return flow, and canal return flow from canal diversion. It was assumed that this total amount of water was used for crop irrigation purposes. The irrigation component of the water balance was subdivided into crop evapotranspiration ( $ET$ ), field tailwater, and deep percolation.

### Valley-scale seasonal aquifer recharge

We used the **water table fluctuation method (WTFM)** for estimating shallow aquifer recharge using water table depth data collected from multiple wells in the Alcalde-Velarde irrigated corridor in the upper portion of the Española Valley. This method determines aquifer recharge based on groundwater level rise and the specific yield of the aquifer. Specific yield is based on physical properties such as the porosity of the aquifer material (for example in gravel versus sandstone). We used 28 wells for measuring water table levels in the Alcalde-Velarde corridor. About half were non-pumping monitoring wells (2 in. diameter) that were installed in the irrigated portion of the valley, and half were domestic wells belonging to collaborators in the dry land portion (Ochoa et al., 2013).

## RESULTS

### Irrigation and deep percolation

In one study looking at the three valley sites, water applied per irrigation ranged from 0.5 to 22 in. depth across the three study sites (Table 1). In general, the greater the irrigation application, the greater the deep percolation values obtained. Deep percolation values obtained were significantly influenced by the changes in soil moisture ( $\Delta S$ ) that were measured from the beginning to 24 hours after the end of irrigation. Wetter soil conditions at the onset of irrigation typically resulted in less  $\Delta S$  and greater amounts of irrigation water moving through the soil profile and percolating below the root zone. In other words, the drier the soil was at the beginning of irrigation, the greater the amount of irrigation water needed to fill the soil profile before water moves below the root zone to add to the groundwater.

Figure 1 shows groundwater level changes during the 2013 irrigation season at our three study sites and illustrates the variability of response among different crop fields. Shallow groundwater levels rose during the irrigation season at all sites. We noted relatively rapid groundwater level rises during most irrigation events. We observed the greater shallow groundwater level response to irrigation deep percolation inputs at

**Table 1. Range of Values for Different Water Budget Components During the 2013 Irrigation Season at the Three Study Sites: El Rito, Rio Hondo, and Alcalde**

Site	IRR (in.)	RO (in.)	PPT (in.)	$\Delta S$ (in.)	AET (in.)	DP (in.)
El Rito	1–22	0.5–8	0–1	0.3–8	0.3–1	0–6
Rio Hondo	0.5–7	0–1	0–1	0–2	0.3–1	0–4
Alcalde	3.4–9	0.2–2	0–0.1	0.5–4	0.3–1	0.1–4

**Note:** Range of values represents six irrigations at the El Rito site, 15 irrigations at the Rio Hondo site, and seven irrigations at the Alcalde site. See Gutierrez-Jurado et al. (2017) for all values. IRR = total irrigation application, RO = runoff, PPT = precipitation,  $\Delta S$  = change in soil moisture, AET = total evapotranspiration, and DP = deep percolation.

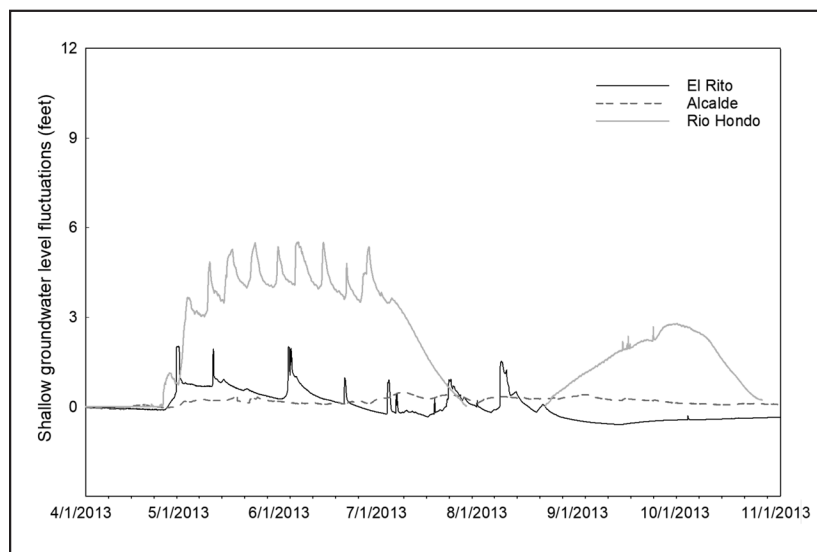
the El Rito site, where groundwater levels rose 7 ft for three of the irrigation events during the season. Soils and subsoil materials have an effect on how rapidly water moved through the soil and into the aquifer. In El Rito in particular, groundwater level rose quickly during irrigation events and also dropped relatively fast as water drained out of the aquifer.

#### Alcalde site water budget

The water budget developed for the Acequia de Alcalde is presented in Table 2. During the three-year period of the study, over half of the water diverted into the acequia returned to the river relatively quickly as surface water. **Desagües** (outlets, turnouts, or sluices) divert water out of acequias as needed to flush plant debris from the acequia at the beginning of the irrigation season, control water flows during the season, or allow upstream users to continue to irrigate if maintenance or repairs are needed downstream of a given desagüe. Large amounts of water exit at the end of the acequia (**acequia outflow**) to return to the river. During normal operation, more water than is needed for irrigation is driven through the acequia to provide sufficient flow so users toward the end of the acequia have enough water to irrigate. Also, in many acequias extra flow helps keep the channel clean from leaves and debris that can obstruct secondary and lateral ditches along the acequia. On average, a third of the water diverted into the Acequia de Alcalde was estimated to have made it to the shallow aquifer after first seeping into the soil of the acequia and crop fields. We assumed

**Table 2. Alcalde Acequia Three-year (2005–2007) Averaged Water Balance (adapted from Fernald et al., 2010)**

		Amount from acequia diversion (%)	
Water balance component		Range	Average
Surface water return flow	Desagüe	0–14	10
	Field tailwater	0–19	9
	Acequia outflow	28–67	41
Shallow aquifer recharge	Acequia seepage	5–17	12
	Deep percolation	9–32	21
Evapotranspiration		1–15	7
<b>Total</b>			<b>100</b>



**Figure 1. Irrigation effects on shallow aquifer recharge, crop field scale (adapted from Gutierrez-Jurado et al., 2017).**

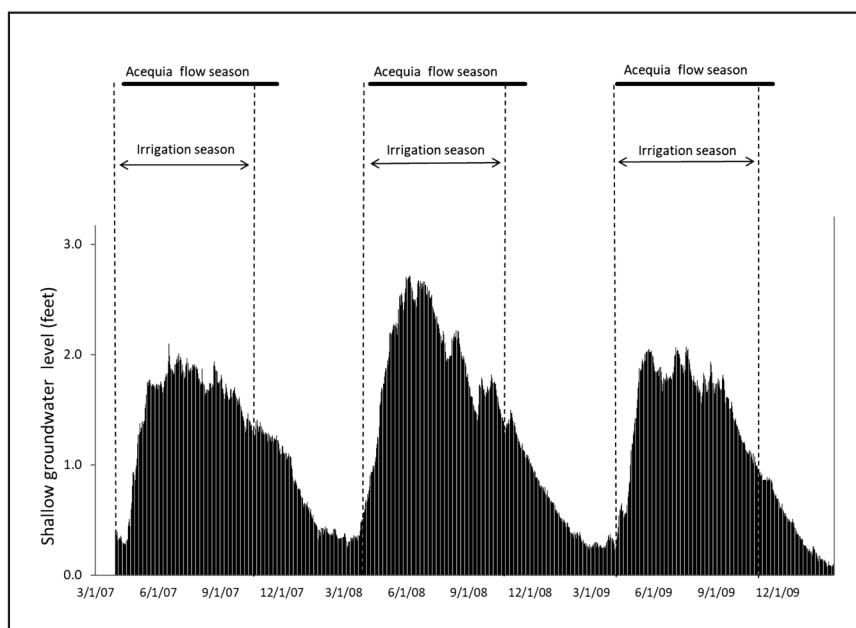
that this water drained back to the river underground, providing delayed groundwater return flow to the river. On average, 7% of the total water diverted into the acequia was used as crop evapotranspiration.

### Seasonal groundwater level fluctuations

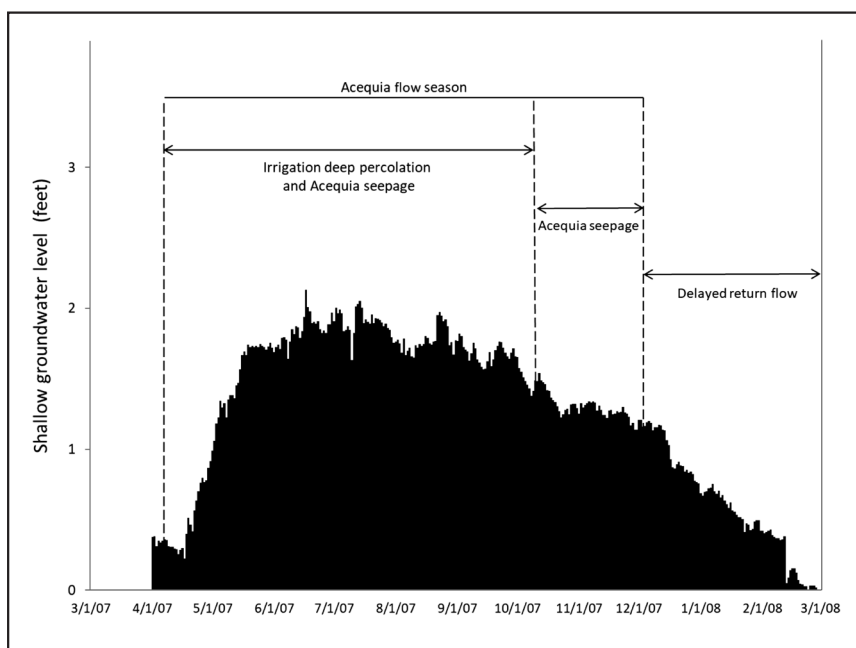
Figure 2 shows three years (2007–2009) of shallow groundwater level data averaged over 28 wells spread across the Alcalde-Velarde valley. It can be observed that groundwater levels started rising after the onset of the irrigation season every year. We used groundwater-level data from all 28 wells to estimate aquifer recharge at the entire Alcalde-Velarde valley scale each year. Aquifer recharge estimates ranged from 3.2 acre-feet (ac-ft)/year in 2009 to 4.1 ac-ft/year in 2008.

Figure 3 shows data for the beginning of the 2008 irrigation season through the beginning of the following season and illustrates shallow groundwater fluctuations as the water management season progresses. After the growing season, when little or no water is diverted to crop fields, the acequias continue to flow for a time to flush out leaves falling from trees along the canals and in some cases as a means to easily water livestock. During this time seepage results primarily via the acequias. When diversion of river water into the acequias ends, groundwater levels continue to drop, indicating drainage of groundwater into the river and thus continued groundwater return flow to the river during the fall and winter months.

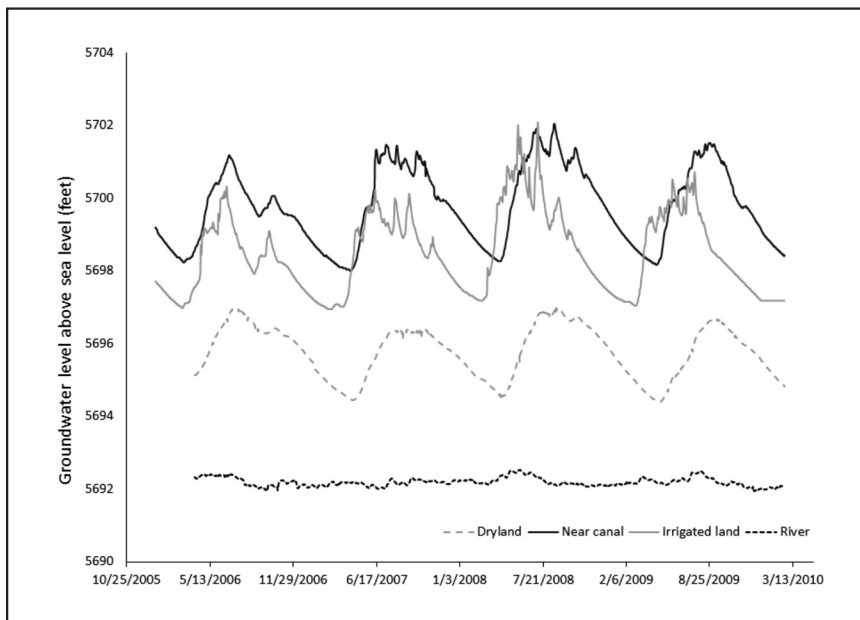
Aquifer recharge in the vicinity of Alcalde, NM, was found to extend beyond the irrigated floodplain (Figure 4). For example, the dryland well in the transect that is located 1,560 ft from the acequia and away from the irrigated floodplain still showed the same seasonal response as the other wells located near the acequia and in the irrigated floodplain. The well in irrigated land



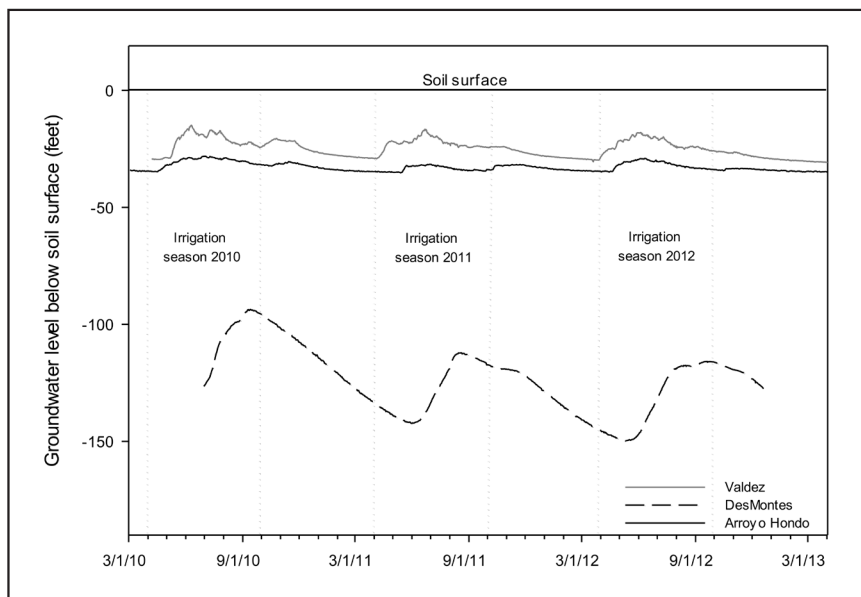
**Figure 2.** Shallow groundwater level fluctuations averaged across 28 monitoring wells in the Alcalde-Velarde valley for years 2007–2009.



**Figure 3.** Shallow groundwater level fluctuations averaged across 28 monitoring wells in the Alcalde-Velarde valley for the 2008 irrigation season through the beginning of the 2009 season. River and acequia canal water levels are based on the Acequia de Alcalde at the NMSU Alcalde Science Center.



**Figure 4.** Water table fluctuations in wells located along one transect at Alcalde, NM. Well distances from the acequia were 1,560 ft (dryland), 10 ft (near canal), 1,240 ft (irrigated land), and 2,735 ft (river).



**Figure 5.** Shallow groundwater level fluctuations from three monitoring wells in the Rio Hondo study site for the 2010 through 2012 irrigation seasons.

exhibited sharp peaks due to specific crop irrigation events. Peaks for the well near the acequia were less defined and were absent in the dryland well.

Figure 5 shows shallow groundwater level fluctuations corresponding to three irrigation seasons (2010, 2011, and 2012) for three different wells at the Rio Hondo site. These wells are located in areas irrigated from three different acequias, which are part of the Rio Hondo system, and represent shallow

groundwater response to irrigation at upstream (Valdez), upper (Des Montes), and downstream (Arroyo Hondo) valley locations along the Rio Hondo. The Valdez and Arroyo Hondo locations are in the narrow valleys alongside the Rio Hondo. The Des Montes site is part of a larger valley at a higher elevation, nearly 100 ft higher, that is not directly connected to the Rio Hondo floodplain. We observed greater groundwater level fluctuations at the Des Montes site, due in part to the larger amount of irrigated land in this valley. Also, we observed a more delayed groundwater level response at this site, which was attributed to the longer time it took the irrigation seepage to reach a deeper groundwater system when compared to the other two sites.

## DISCUSSION

Aquifer recharge and groundwater return flow are two important hydrologic benefits resulting from acequia agriculture in the region. Delayed groundwater return flow to the river is especially of interest because of the benefits of maintaining river flows for downstream users—including irrigators, municipalities, and riparian vegetation and the associated wildlife—and their needs. In other regions, situations exist where expensive projects are carried out to artificially recharge the aquifer to provide streamflow late in the season. In Northern New Mexico, recharge occurs as a byproduct of traditional irrigation techniques. When aquifer recharge extends into the dryland area above the floodplain, it is important not only for shallow wells of property owners but also for the higher yield community wells.

Various factors determine whether irrigation seepage is beneficial or detrimental in a given location. At the three different study sites we investigated, we encountered relatively rapid shallow aquifer recharge and gaining river conditions, which may help with the return of subsurface



flows back to the river. We attributed this in part to the permeable soil conditions and flood irrigation practices commonly found in all three sites, which may have helped with the rapid movement of irrigation water through the soil profile, then into the aquifer, and lastly back to the river. In the case of a losing river, where the river drains into the aquifer system, any loss of seepage out of canals or via deep percolation below fields may not become return flow and reach the river to augment flows.

Currently in Northern New Mexico, freshwater is generally of high quality, and there is limited use of pesticides or even synthetic fertilizers. Therefore, the irrigation seepage contributions to aquifer recharge and return flow are of good quality. An additional benefit of these high-quality subsurface flows is that irrigation seepage mixes with groundwater during the irrigation season and serves to dilute undesirable ions such as nitrate (Helmus et al., 2009). In cases where agriculture is chemical-intensive, irrigation seepage can carry pesticides and/or excess nutrients to the groundwater and the stream, and it is important in these situations to strive to prevent irrigation seepage.

If irrigated agriculture declines or is significantly altered in Northern New Mexico, it is unclear how the Rio Grande hydrograph will change, although it will likely mean decreased river flows after the season of spring mountain runoff. Despite irrigation systems not being a natural feature of the landscape, it could be argued that irrigated agriculture maintains hydrologic aspects more similar to the original natural system than if irrigation were to cease. Due to human-made changes to the river systems, including channelization and construction of flood-control levees, streams no longer meander to the extent they did or flood into side channels or the floodplain as before (processes that naturally meant more seepage of water into the floodplain, more aquifer recharge, and thus more late-season groundwater return flow). Long-term drought would of course also affect aquifer recharge and streamflow patterns not only as a direct result of less precipitation but also because of the likely socioeconomic and policy changes that would result and that could affect water management and distribution.

## CONCLUSIONS

Given the growing concern regarding future water supplies in arid and semiarid regions, it is important to increase our understanding of the hydrology of irrigated agriculture. Agricultural production in most acequia irrigated valleys in New Mexico is relatively small when compared to many other irrigated agricultural regions in the United States (e.g., California). However, aquifer recharge and late-season groundwater return flow are important hydrologic functions that result from acequia agriculture. These functions provide important hydrologic benefits to downstream municipalities and irrigated agriculture as well as riparian areas, adding importantly to the value of acequia agriculture. These hydrologic functions could become even more im-

portant in the event of long-term drought. By understanding the hydrology of representative acequia valleys in Northern New Mexico, we will be better prepared to manage these traditional agricultural systems and maintain local aquifer recharge in a future with increased demands for water and drought-constrained supplies.

In the studies presented in this chapter, we were able to document important hydrologic processes in acequia agricultural systems of Northern New Mexico and their implications for water quality and water provisioning in this water-scarce region of the southwestern United States. Results from this hydrology research are currently being used in larger scale models that incorporate different social and climate scenarios (Gunda et al., 2018; Turner et. al., 2016).

## ACKNOWLEDGMENTS

Authors gratefully acknowledge the technical assistance of the NMSU Alcalde Science Center staff, especially David Archuleta, Val Archuleta, David Salazar, Estevan Herrera, and Robert Heyduck. This material is based upon work supported by the U.S. Department of Agriculture Cooperative State Research, Education and Extension Service under Agreement No. 2005-34461-15661 and 2005-45049-03209, by the National Science Foundation Award No. 0814449 and Award No. 1010516, and by the New Mexico State University Agricultural Experiment Station.

## REFERENCES

- Cruz, J.J., D.M. VanLeeuwen, A.G. Fernald, S.J. Guldan, and C.G. Ochoa. 2018. River-ditch hydrologic connections in a traditionally irrigated agricultural valley in New Mexico. *Journal of Irrigation and Drainage Engineering*, 144.
- Cruz, J.J., A.G. Fernald, D.M. VanLeeuwen, S.J. Guldan, and C.G. Ochoa. 2019. River-ditch flow statistical relationships in a traditionally irrigated valley near Taos, New Mexico. *Journal of Contemporary Water Research & Education*, 168, 49–65.
- Fernald, A.G., S.Y. Cevik, C.G. Ochoa, V.C. Tidwell, J.P. King, and S.J. Guldan. 2010. River hydrograph retransmission functions of irrigated valley surface water-groundwater interactions. *Journal of Irrigation and Drainage Engineering*, 136, 823–835.
- Frisbee, M.D., D.G. Tolley, and J.L. Wilson. 2017. Field estimates of groundwater circulation depths in two mountainous watersheds in the western U.S. and the effect of deep circulation on solute concentrations in streamflow. *Water Resources Research*, 53, 2693–2715.
- Frisbee, M.D., E.H. Tysor, N.S. Stewart-Maddox, L.M. Tsinnajinnie, J.L. Wilson, D.E. Granger, and B.D. Newman. 2016. Is there a geomorphic expression of interbasin groundwater flow in watersheds? Interactions between interbasin groundwater flow, springs, streams, and geomorphology. *Geophysical Research Letters*, 43, 1158–1165.

- Gunda, T., B.L. Turner, and V.C. Tidwell. 2018. The influential role of sociocultural feedbacks on community-managed irrigation system behaviors during times of water stress. *Water Resources Research*, 54, 2697–2714.
- Gutiérrez-Jurado, K.Y., A.G. Fernald, S.J. Guldán, and C.G. Ochoa. 2017. Surface water and groundwater interactions in traditionally irrigated fields in Northern New Mexico, U.S.A. *Water*, 9, 102.
- Helmus, A.M., A.G. Fernald, D.M. VanLeeuwen, L.B. Abbott, A.L. Ulery, and T.T. Baker. 2009. Surface water seepage effects on shallow ground-water quality along the Rio Grande in Northern New Mexico. *Journal of the American Water Resources Association*, 45, 407–418.
- Johnson, P.S., P.W. Bauer, and B. Felix. 2009. Hydrogeologic investigation of the Arroyo Hondo area, Taos County, New Mexico: Final technical report prepared for Taos County/New Mexico Bureau of Geology and Mineral Resources [505]. Socorro: New Mexico Institute of Mining and Technology.
- Ochoa, C.G., A.G. Fernald, S.J. Guldán, and M.K. Shukla. 2007. Deep percolation and its effects on shallow groundwater level rise following flood irrigation. *Transactions of the ASABE*, 50, 73–81.
- Ochoa, C.G., A.G. Fernald, S.J. Guldán, and M.K. Shukla. 2009. Water movement through a shallow vadose zone: A field irrigation experiment. *Vadose Zone Journal*, 8, 414–425.
- Ochoa, C.G., A.G. Fernald, S.J. Guldán, V.C. Tidwell, and M.K. Shukla. 2013. Shallow aquifer recharge from irrigation in a semiarid agricultural valley in New Mexico. *Journal of Hydrologic Engineering*, 18, 1219–1230.
- Scanlon, B.R., R.W. Healy, and P.G. Cook. 2002. Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeology Journal*, 10, 18–39.
- Stephens, D.B., and Associates, Inc. 2003, March. Jemez y Sangre regional water plan. Retrieved September 19, 2019, from [https://allaboutwatersheds.org/new-mexico-water-dialogue/library/documents/jys\\_sec1-5.pdf](https://allaboutwatersheds.org/new-mexico-water-dialogue/library/documents/jys_sec1-5.pdf)
- Turner, B., V. Tidwell, A. Fernald, J. Rivera, S. Rodríguez, S. Guldán, C. Ochoa, B. Hurd, K. Boykin, and A. Cibils. 2016. Modeling acequia irrigation systems using system dynamics: Model development, evaluation, and sensitivity analyses to investigate effects of socio-economic and biophysical feedbacks. *Sustainability*, 8.
- United States Geological Survey (USGS). 2019. Surface-water annual statistics for the nation, USGS 08279500 RIO GRANDE AT EMBUDO, NM. Retrieved March 4, 2019, from <https://waterdata.usgs.gov/nwis/annual>
- Western Regional Climate Center. 2006. Alcalde, New Mexico (290245), period of record monthly climate summary, period of record 04/01/1953–12/31/2005. Retrieved March 6, 2019, from <http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nmalca>

# The Role of Livestock in Supporting Acequia Communities of Northern New Mexico<sup>1</sup>

Stephanie C. López, Andrés F. Cibils, Lilian Cibils,  
Ursula R. Smedly, Steve J. Guldán, Sam Fernald,  
Carlos G. Ochoa, and Kenneth G. Boykin

---

## INTRODUCTION

Roughly half of the world's food is produced by small-holder **agropastoralists** who grow crops on small parcels of land and use native rangeland and crop residues (plant parts left in the field after crop harvest; e.g. straw, stems) to raise a few head of livestock (Herrero et al., 2010).

In many of these systems, livestock serve the purpose of alleviating poverty (Thornton et al., 2003), particularly in family-based subsistence agriculture (Alary et al., 2011). Similar to what occurs in other agropastoral economies worldwide (Herrero et al., 2010), Hispanic settlers in semiarid New Mexico relied on livestock to ensure food security during periods of drought (Eastman and Gray, 1987; Dunmire, 2013). Spanish colonial community land grants in the region were deliberately designed to support small-scale agropastoral economies (Rivera, 1998). Settler families were granted a *solar*, a small privately owned parcel of land on the non-irrigated side of an *acequia*, to build their homes, and were awarded acreage of adjacent rangeland, known as *cuarentas*, intended to provide sufficient forage to sustain a dairy cow or to occasionally grow dryland crops (Eastman and Gray, 1987). In addition, settlers had access to communal, abutting upland forests and woodlands where members of the land grant had both grazing and firewood gathering rights (Eastman and Gray, 1987). Consequently, rangeland-based livestock raising became intricately woven into the acequia economy and deeply rooted in the cultural tradition of its members (Rivera, 1998).

Although a few land grants still exist in New Mexico today (Eastman et al., 2000; Ebright, 1994; United States Government Accountability Office [U.S. GAO], 2001), most acequias lost local control of common grazing lands during the late 19th and early 20th centuries when common ownership ceased to be recognized as legal, and upland forests and rangelands were placed primarily under the jurisdiction of the United States Forest Service (USFS) (Raish and McSweeney, 2008) or the United

States Department of the Interior's Bureau of Land Management (BLM) (Ebright, 1994). Today, many land grant heirs who still practice acequia irrigation farming in the valleys pay grazing fees to use public lands, formerly common pastoral areas, to sustain their livestock (Raish and McSweeney, 2008). Federal land management agencies have sought to accommodate traditional customs by providing Hispanic land grant heirs priority on land leasing or allowing multiple user permits on allotments<sup>2</sup> (Eastman et al., 2000; Raish and McSweeney, 2008), but controversy and litigation over land tenure rights persist (Tucker, 2012; Schultz, 2013). Government imposed shifts in grazing rights on common lands are a frequent stressor in pastoral systems worldwide (Reid et al., 2014), including the Western United States, where ranching enterprises have been historically shaped by periods of land tenure stability and instability as a result of fluctuation from communal use to private property to government-regulated public ownership regimes (Huntsinger et al., 2010). Acequia communities adapted to the loss of local control of common grazing lands and maintained pastoral activities, which are still thought to be locally important to the livelihood of some communities (Cox, 2010). However, contemporary region-wide assessments of the role of rangeland-based livestock raising in sustaining acequia farming are lacking.

The objective of this study was to assess the role of livestock raising in supporting traditional acequia agropastoral communities of north-central New Mexico. More broadly, we sought to understand valley-upland connections and their contribution to the apparent resilience of acequia communities. We define resilience following Walker et al. (2004) as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks."

## METHODS

Our study area included acequia farming communities and adjacent upland grazing allotments located within Rio Arriba and Taos Counties in north-central New Mexico, close to the localities of Alcalde (36.09°N, 106.06°W), El Rito (36.32°N, 106.16°W), and Rio Hondo-Valdez (36.53°N, 105.56°W). Alcalde is a small community that lies on the east side of the Rio Grande, neighboring public grazing lands managed by the BLM. El Rito, surrounded by the Carson National Forest, was one of the first Spanish settlements of Northern New Mexico (Pearce, 1980) and is located on a tributary of the Rio Chama. Lastly, the paired community of Rio Hondo-Valdez is located north of Taos valley on a tributary of the Rio Grande. This community rests at the foot of the Sangre de Cristo Mountains, bordering the Carson National Forest. Each site supports livestock production on both private and public grazing lands (Eastman et al., 1997; Eastman and Gray, 1987). The communities of Alcalde, El Rito, and Rio Hondo-Valdez were selected because they a) encompass the regional variation in river hydrological regimes available in the region (Alcalde is on the main stem of the Rio Grande, while the other two sites occur on tributaries<sup>3</sup>), and b) include communities that continue to practice traditional acequia irrigation, maintaining traditional community-based water governance customs and institutions.

Annual average maximum and minimum temperatures in Alcalde are 68.2°F and 34°F, respectively. Total annual rainfall is roughly 10.12 in. (“Climate of New Mexico,” n.d.). In El Rito, annual average maximum and minimum temperatures are 64.8°F and 37.2°F, respectively, and total annual rainfall is 9.9 in. (“Climate of New Mexico,” n.d.). For Rio Hondo-Valdez, the annual average maximum and minimum temperatures are 63.7°F and 31.1°F, respectively, and total annual rainfall is approximately 12.3 in. (“Climate of New Mexico,” n.d.). July and August are the wettest months at all sites; 30–40% of the year’s total precipitation occurs during that time of the year (“Climate of New Mexico,” n.d.). The entire region is exposed to periodic droughts of varying duration and intensity.

We developed a questionnaire based on unstructured informal interviews with community leaders and in consultation with a multidisciplinary research team comprised of agronomists, anthropologists, county Extension agents, economists, hydrologists, rangeland scientists, and rural sociologists. Professionals from the USFS and the BLM, as well as members of the Northern New Mexico Stockman’s Association and the Taos Valley Acequia Association, provided input on the final version of the questionnaire. Because this study set out to identify the linkages between irrigated land use in the valley (acequia farming) and rangeland grazing in the upland, it was established that the population of interest consisted of small-scale livestock operators who owned irrigated farmland and had grazing permits on federal grazing lands. Surveyed respondents met at least

one of the following three criteria: small-scale livestock operators who own irrigated farmland, and/or have grazing permits on federal grazing lands, and/or are members of an acequia and/or grazing association.

Approximately half the surveys were handed out at the Northern New Mexico Stockman’s Association annual meeting in Taos in January 2013. This meeting is typically attended by ranchers and farmers with small- to mid-sized livestock operations, most of whom are members of traditional Hispanic farming and ranching communities of the region. This portion of our survey involved using the time-location sampling strategy that targets “everyone present at a particular location during a particular time period” (Patton, 2014). Shortly thereafter, New Mexico State University Cooperative Extension Service employees personally delivered the remaining questionnaires to farming households with the aid of using the **chain referral method** (Bernard, 2006). The first stage in this method consisted of finding and contacting a household who met at least one of the target population criteria. Once the survey was completed, individual(s) were asked to help identify and introduce us to other individuals with similar characteristics or from the same subgroup of the population (Bernard, 2006; Bailey, 1978). Therefore, survey participants included local community leaders, farmers, and ranchers from Taos valley and from the Alcalde, El Rito, and Rio Hondo-Valdez areas.

The questionnaire included 27 multiple choice and five modified Likert-scale questions (a common type of rating scale used to assess attitudes or opinions), which were divided into three main sections: 1) respondent demographics (age, gender, heritage, occupation, income source, and community participation), 2) farm/ranch operation characterization (livestock type, herd/flock size, summer grazing and winter feeding management, animal production marketing, size of farming operation, and crops grown), and 3) strategies and perceptions (drought and herd liquidation coping strategies, livestock contribution to income, family tradition, benefits of acequia membership, and access to public grazing lands).

## RESULTS

A total of 74 questionnaires were completed by participants who were either 1) present at the Northern New Mexico Stockman’s Association annual meeting (n=49) or 2) who were visited in their homes (n=25) in the El Rito (n=15), Rio Hondo-Valdez (n=6), and Alcalde (n=4) study areas. All participants met at least one of our three selection criteria described above.

### Survey participants

Ninety-five percent of surveyed participants raised livestock. Most raised cattle only, whereas a few respondents (15%) raised both cattle and sheep. Cow-calf operations were the most common livestock enterprise (80% of respondents). Fifty-two percent of the surveyed respondents



declared herds of less than 50 head of cattle; two-thirds of these participants owned 20 head or less. Seventy-four percent of respondents that raised sheep and cattle owned flocks of less than 25 head of sheep. Eighty-three percent of surveyed participants described themselves as “hands on” managers, and more than two-thirds (68%) indicated that their families helped with livestock management chores on a regular basis.

Sixty-six percent of respondents had grazing permits on public grazing lands. Most of these individuals grazed both public and private lands (public primarily in summer and private primarily in winter), whereas a minority (6%) depended solely on public grazing lands. Sixty-eight percent of respondents that had grazing permits on public grazing lands held a joint permit on the grazing allotment (i.e., their livestock were part of a multiple-owner herd/flock). Sixty-four percent of respondents that had grazing permits on public grazing lands owned a base property (privately owned land, usually the farm/ranch headquarters) located less than 30 miles from the grazing allotment.

Half of respondents who raised livestock reported that their herd/flock size had decreased over the past 15 years. The remaining half was evenly divided between those reporting no change and those who had increased the size of their herd/flock. The single most frequently cited factor (42%) limiting respondents’ ability to increase herd/flock numbers was the capacity to grow or purchase hay to feed livestock during winter months. Droughts and availability of summer grazing lands, on the other hand, were the least frequently cited factors (18% and 6%, respectively).

More than half of the surveyed population who farmed irrigated land (n=65; 58%) owned more than 20 acres (ac) of farmland. Thirty-one percent owned 5–20 ac of irrigated land, and a small proportion of respondents (11%) owned less than 5 ac. Most respondents that owned irrigated land grew hay (91%); most used it as forage for their livestock (77%), but in a few cases (14%) hay was grown mostly for sale.

### Strategies to cope with drought

The most frequent strategy adopted by survey participants to cope with drought consisted of a combination of purchasing or storing forage and reducing herd numbers (Figure 1). Purchasing forage and selling livestock were the most and least utilized strategies, respectively (Figure 1). Respondents who were members of **acequia associations** were the most likely to store forage reserves, whereas members of grazing associations were more likely to purchase hay. Respondents with intermediate cattle herds (20–50 head) were more likely to sell livestock in a drought, whereas participants with small (<20 head) and large (>50 head) herds were more likely to either store (small herds) or purchase (large herds) forage to cope with droughts. Individuals whose livestock grazed on private lands were the most likely to sell livestock in a drought. Conversely, individuals who had grazing permits on public grazing lands were more

prone to feed forage, either stored or purchased, to mitigate the effects of drought. Respondents with “hands on” management styles (i.e., farmers/ranchers who were directly involved in the day-to-day management of their livestock) were more likely to adopt a mix of strategies involving both feeding and culling to cope with drought, whereas individuals with “hands off” (i.e., hired others to manage their livestock) or a mix of hands on/off management styles were less likely to sell livestock and more prone to feed either purchased or stored forage.

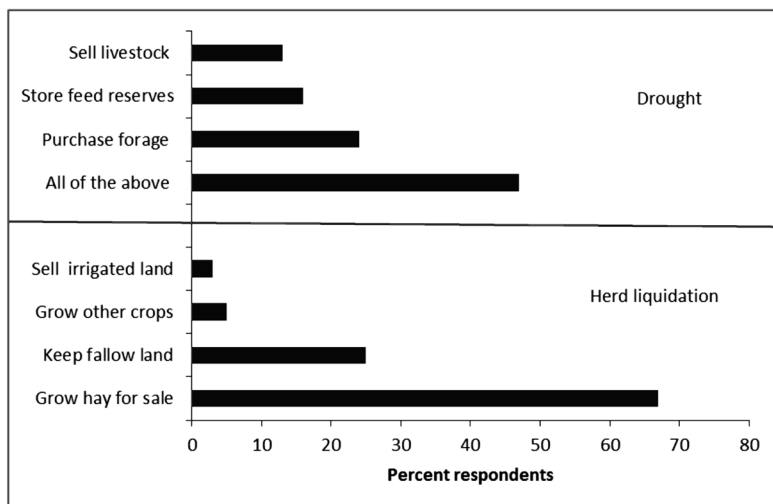
If individuals had no choice but to liquidate their livestock, 97% of respondents indicated that they would be unwilling to sell their farmland (Figure 1). Sixty-six percent would continue to grow hay for sale, a quarter would give up farming but maintain ownership of their fallow irrigated farmland, whereas a minority (5%) would grow other crops (Figure 1). Only respondents who self-identified as ranchers, or whose herd numbers had declined over the past 15 years, were likely to sell their irrigated farmland if forced to liquidate their livestock. Those who self-identified as farmers, rancher/farmers, retirees, other, or whose herd numbers had increased over the past 15 years were much more likely to maintain ownership of their lands and, in most cases, grow hay for sale.

Respondents who raised both sheep and cattle were more likely to either sell their land or grow crops other than hay if forced to sell off all their livestock. All participants owning small farms (<20 ac) would adopt strategies that did not involve losing farm ownership, whereas a minority of larger farm owners would consider selling their land if forced to sell off all their livestock. Small farm owners were much more likely to maintain their farms fallow compared with large farm respondents who were more likely to grow hay for sale. Only respondents who currently grew hay to feed their livestock indicated that they would consider selling their irrigated land if forced to liquidate their herd.

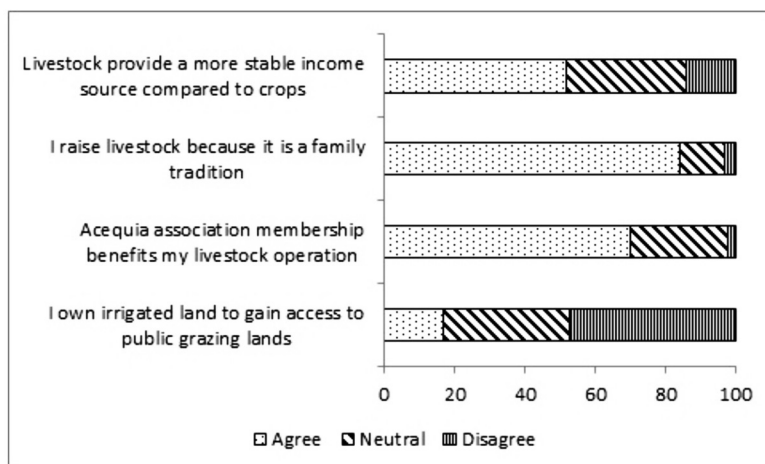
### Role of livestock

Slightly more than half of participants surveyed agreed that owning livestock provides better financial security than growing irrigated crops; very few respondents (13%) disagreed with this notion (Figure 2). Respondents who self-identified as farmers, who owned small herds of cattle (<50 head), or who grazed livestock close to their base property (<30 miles) were more likely to disagree with the view that livestock provide better financial stability than crops. Conversely, participants who described themselves as being both a farmer and a rancher, who owned a large herd of cattle (>50 head), or whose grazing lands were far from the base property (>30 miles) were the groups who supported this idea the most.

Most surveyed individuals who grazed their livestock close to their base property (<30 miles) also declared off-farm income as their most important source of livelihood.



**Figure 1. Strategies of agropastoralists of our study area in north-central New Mexico to cope with drought (above) and livestock herd liquidation (below).**



**Figure 2. Perceptions of agropastoralists of our study area in north-central New Mexico regarding the role of livestock (top two bars) and the links between irrigated farming and livestock production (bottom two bars).**

Eighty-four percent of surveyed individuals agreed that livestock raising was a family tradition (Figure 2). Most participants indicated that their involvement in an acequia association was beneficial to their livestock operation, and very few respondents viewed access to public grazing lands as a driving motive to own irrigated lands (Figure 2).

## DISCUSSION

Regardless of whether participants self-identified as farmers, ranchers, or both, 95% of survey respondents raised livestock (mostly cow-calf), 90% of participants who owned irrigated land grew hay (mostly to feed their live-

stock), and close to two-thirds of participants paid grazing fees to the federal government to graze their livestock during part of the year. A majority of the latter held joint grazing permits and were members of acequia and/or grazing associations. As in the early days of Spanish colonial settlement, contemporary acequia communities continue to rely on agricultural endeavors that involve strategic integration of upland and valley natural systems. Current day small-scale pastoral enterprises (52% of respondents owned less than 50 head of cattle) appear to not only provide a means of connecting the use of these two types of land but also of maintaining family traditions and fostering community cohesiveness, both of which emerged as important cultural values among survey participants in this and in previous studies (Eastman and Gray, 1987; Eastman et al., 2000; McSweeney and Raish, 2012; Dunmire, 2013).

## Livestock as financial security

More than half of survey participants in our study agreed with the notion that raising livestock provides better financial security than growing crops. For most farmers engaged in smallholder agropastoralism worldwide, livestock are not only a tradeable commodity but also serve as a preferred wealth store (Roncoli et al., 2007; Turner, 2009), a source of cash in hand to cover household emergencies (Alaryet al., 2011), or as an insurance to mitigate the consequences of crop loss during droughts (Turner et al., 2014). Similarly, small-scale Hispanic farmers of Northern New Mexico view livestock “as banks-on-the-hoof, which can be used in hard times” and that serve “as a back-up resource for emergencies, for periods of unemployment, or for special needs such as college tuition for the children” (Eastman et al., 2000).

In small-scale agropastoral systems worldwide, income from crops usually outweighs livestock contributions to the household economy (Herrero et al., 2010). Conversely, acequia farmers in our study area appear to have become increasingly less food crop-reliant and more engaged in growing hay crops to feed livestock. Historically, acequia communities grew a wider variety of crops, including beans, wheat, maize, and alfalfa (Eastman et al., 2000), but throughout the second half of the 20th century, in some valleys parcels of farmland became larger (Fernald et al., 2015) and the percentage of irrigated land used to grow hay, par-

ticularly alfalfa, increased steadily (Ortiz et al., 2007). Less than 10% of survey respondents in this study grew crops other than hay, and when asked about preferred strategies in an extreme situation of forced herd liquidation, very few participants (5%) viewed switching to other crops as a viable alternative. Rather, most survey respondents indicated that they would continue to grow hay for sale. The fact that for most respondents off-farm employment or retirement was the main source of family income, a phenomenon somewhat analogous to out-migrant remittances in developing world agropastoralism (e.g., Deshingkar, 2012; Davis and Lopez-Carr, 2014), perhaps explains the transition toward less time-consuming pastoral-based farming systems.

### **Community resilience**

Despite a historical sharp decline in public land grazing permits (Fernald et al., 2015; Eastman et al., 2000), a fact often cited in land tenure litigations (Ebright, 1994), only half of survey respondents reported that their herd/flock numbers had decreased over the past 15 years. The remaining half was evenly divided between those reporting no change (25%) and those who had seen an increase in the size of their herd/flock (25%). Recent herd dynamics, however, were significantly associated with a respondent's apparent willingness to sell their ancestral irrigated land and presumably abandon the acequia-centered lifestyle if forced to liquidate their livestock. The very few respondents (3%) who expressed willingness to sell their farmland were individuals who had seen their livestock herd wane in recent years. This finding, while numerically minor, might not be trivial in terms of community resilience. Further research is needed to determine the connections between loss of livestock and the decision to abandon acequia farming in the region.

### **Hay as the main limiting factor**

Given the long history of litigation over rangeland tenure rights between heirs of Spanish and Mexican land grants and the federal government (Eastman and Gray, 1987; Eastman et al., 2000; Raish and McSweeney, 2008; Ebright, 1994), we were surprised to find that availability of summer grazing lands (almost entirely public lands) was the least frequently cited factor (6% of responses) limiting respondents' ability to increase the size of their livestock herds. The capacity to grow or purchase hay to feed livestock through the winter months was the single most frequently cited factor (42% of responses). Although winter or dry season forage bottlenecks are common in most pasture-based livestock systems around the world (Neely et al., 2010), and even though it is well known that supplement feed is the costliest element of rangeland-based cow-calf operations (Holechek et al., 2011), the apparent central role of hay in regulating livestock numbers across our study area (as shown in our historical data analyses) was somewhat unexpected.

### **Significance of valley-upland spatial connectivity**

The Nobel Prize winning economist Elinor Ostrom (1990) highlighted the case of communal grazing land tenure of high-altitude meadows and forests of Tröbel, Switzerland. In those systems, which date back to the 13th century, farmers plant crops (including hay) on privately owned land and communally graze the uplands. Interestingly, upland grazing regulations established as early as the 16th century stipulated that “no citizen could send more cows to the alp than he could feed during the winter” (Netting, 1976), a land use practice that is thought to explain why these agropastoral communities were able to endure centuries of socio-ecological change. The New Mexico acequia systems we studied appeared to exhibit some of the core elements of the secret to Tröbel's endurance (Ostrom, 1990)—i.e., production of forage for winter use appeared to regulate levels of summer livestock herbivory in the upland. Initially, public land permits in the U.S. had similar stipulations to those of Tröbel; however, the Swiss agropastoral villages (Ostrom, 1990) and the systems we studied are possibly different in terms of spatial connectivity of agricultural production of valleys and adjacent uplands. Only about a third of survey respondents (data not shown) in our study grazed their livestock on public lands within 10 miles of their base property (irrigated land).

We suspect that since the days of Spanish and Mexican land grants (Eastman and Gray, 1987), acequia pastoralism has experienced increasing spatial decoupling of valley farming and upland grazing. This phenomenon might be partly to blame for patterns of land tenure litigation and conflict observed in our study area. If, as our data suggest, upland stocking rates are mostly regulated by the ability of farmers to feed their livestock through the winter, El Rito would have been the site where valley regulation of upland stocking rates should have been strongest. Yet associations of permittees who graze their livestock on allotments above El Rito have exhibited the highest levels of litigation and opposition to USFS grazing regulations in the recent past (e.g., Schultz, 2013). Although base property location analysis was not included in our study, it is possible that an increasing number of these permittees own base properties outside of the El Rito valley, the least productive of our study sites. This valley-upland decoupling has possibly led to a situation of relaxed winter forage constraints, increased demand for summer forage on public lands, and a logical increase in the levels of litigation and conflict. Interestingly, allotments above El Rito were the only ones to show an increase in stocking rates over the past 30 years. Further research will be needed to determine the connections between spatial proximity of valley hay production and upland grazing lands and the resilience of acequia agropastoral systems.



## CONCLUSIONS

The resilience of the acequia systems we studied appears to depend on close connection of uplands and valleys. At the most basic level, hydrological connection between the upland watershed and downstream valleys allows for crop/hay production and household water provisioning (Ochoa et al., 2013). Spatial connectivity is obviously essential at this level. At another level, there appear to be livestock-mediated connections that allow integrating forage productivity of upland rangelands and downstream valleys. Increased snowmelt in the upland forests yields more water in the valley acequias, leading to higher hay production, which can promote growth in livestock numbers. The opposite occurs in years of water scarcity. This agro-biophysical feedback loop perhaps lies at the core of the resilience and sustainability of traditional agropastoral communities of Northern New Mexico. Spatial decoupling of valley and adjacent rangeland agricultural activities could short-circuit this hypothesized water-mediated feedback loop and cause a breakdown in the system's ability to self-regulate and persist, a phenomenon that should be considered in future allocation of public rangeland livestock grazing permits.

## ENDNOTES

1. This chapter was adapted from López et al., 2018. Linkages between acequia farming and rangeland grazing in traditional agropastoral communities of the Southwestern USA. *Sustainability*, 10, 2021.
2. An allotment is “a rangeland and/or forested area designated for the use of a prescribed number and kind of livestock under one plan of management” (Holechek et al., 2011).
3. El Rito represents an area with lower streamflow, whereas Rio Hondo-Valdez is in an area with higher snowpack and streamflow.

## ACKNOWLEDGMENTS

This research was funded with a grant from the National Science Foundation Coupled Natural and Human Systems Program (#1010516 to Fernald et al.). Partial support was provided by the New Mexico State University Agricultural Experiment Station, United States Department of Agriculture, and National Institute of Food and Agriculture Hatch Project 1000985 (Cibils). Authors wish to thank Drs. Lee Hamilton, Vince Tidwell, José Rivera, Sylvia Rodríguez, and Brian Hurd, and Mr. David Archuleta, Tony Valdez, Pat Torres, Edmund Gomez, John Miera, and Palemón Martinez for invaluable comments and suggestions that greatly improved our survey instrument. The Northern New Mexico Stockman's Association generously provided the opportunity for us to deliver surveys at their 2013 annual meeting in Taos, and Mr. Joseph Garcia and Tony Valdez were instrumental in helping us conduct surveys among farmers in our study area.

## REFERENCES

- Alary, V., C. Corniaux, and D. Gautier. 2011. Livestock's contribution to poverty alleviation: How to measure it? *World Development*, 39, 1638–1648.
- Bailey, K.D. 1978. *Methods of social research*. New York, NY: Free Press.
- Bernard, H.R. 2006. *Research methods in anthropology: Qualitative and quantitative approaches*, 4th ed. Lanham, MD: AltaMira Press.
- Climate of New Mexico. n.d. Western Regional Climate Center. Retrieved June 14, 2018, from <https://wrcc.dri.edu/narratives/NEWMEXICO.htm>
- Cox, M. 2010. *Exploring the dynamics of social-ecological systems: The case of the Taos valley acequias* [doctoral dissertation]. Retrieved from Digital Library of the Commons. Indiana University, Bloomington, IN.
- Davis, J., and D. Lopez-Carr. 2014. Migration, remittances and smallholder decision-making: Implications for land use and livelihood change in Central America. *Land Use Policy*, 36, 319–329.
- Deshingkar, P. 2012. Environmental risk, resilience and migration: Implications for natural resource management and agriculture. *Environmental Research Letters*, 7(1). doi: 10.1088/1748-9326/7/1/015603
- Dunmire, W.W. 2013. *New Mexico's Spanish livestock heritage: Four centuries of animals, land, and people*. Albuquerque: University of New Mexico Press.
- Eastman, C., and J.R. Gray. 1987. *Community grazing: Practice and potential in New Mexico*, 1st ed. Albuquerque: University of New Mexico.
- Eastman, C., J.P. King, and N.A. Meadows. 1997. Acequias, small farms, and the good life. *Culture & Agriculture*, 19, 14–23.
- Eastman, C., C. Raish, and A. McSweeney. 2000. Small livestock operations in northern New Mexico. In R. Jamison and C. Raish (Eds.), *Livestock management in the American Southwest: Ecology, society, and economics*. Amsterdam, The Netherlands: Elsevier.
- Ebright, M. 1994. *Land grants and lawsuits in northern New Mexico*, 1st ed. Albuquerque: University of New Mexico Press.
- Fernald, A., S. Guldán, K. Boykin, A. Cibils, M. Gonzales, B. Hurd, S. Lopez, C. Ochoa, M. Ortiz, J. Rivera, S. Rodriguez, and C. Steele. 2015. Linked hydrologic and social systems that support resilience of traditional irrigation communities. *Hydrology and Earth System Sciences*, 19, 293–307.
- Herrero, M., P.K. Thornton, A.M. Notenbaert, S. Wood, S. Msangi, H.A. Freeman, D. Bossio, J. Dixon, M. Peters, J. van de Steeg, J. Lynam, P. Parthasarathy Rao, S. Macmillan, B. Gerard, J. McDermott, C. Seré, and M. Rosegrant. 2010. Smart investments in sustainable food production: Revisiting mixed crop-livestock systems. *Science*, 327, 822–825.



- Holechek, J.L., R.D. Pieper, and C.H. Herbel. 2011. *Range management principles and practices*, 6th ed. Upper Saddle River, NJ: Prentice Hall.
- Huntsinger, L., L.C. Forero, and A. Sulak. 2010. Transhumance and pastoralist resilience in the Western United States. *Pastoralism*, 1, 9–36.
- López, S.C., A.F. Cibils, U.R. Smedly, S.J. Guldán, A.G. Fernald, C.G. Ochoa, K.G. Boykin, and L. Cibils. 2018. Linkages between acequia farming and rangeland grazing in traditional agropastoral communities of the Southwestern USA. *Sustainability*, 10, 2021.
- McSweeney, A.M., and C. Raish. 2012. Social, cultural, and economic aspects of livestock ranching on the Santa Fe and Carson National Forests [RMRS GTR 276]. Fort Collins, CO: USDA/USFS.
- Neely, C., S. Bunning, and A. Wilkes. 2010. Managing dryland pastoral systems: Implications for mitigation and adaptation to climate change. In M. Abberton, R. Conant, and C. Batello (Eds.), *Grassland carbon sequestration: Management, policy and economics* (pp. 235–266). Rome, Italy: FAO.
- Netting, R.M. 1976. What alpine peasants have in common: Observations on communal tenure in a Swiss village. *Human Ecology*, 4, 135–146.
- Ochoa, C.G., A.G. Fernald, S.J. Guldán, V.C. Tidwell, and M.K. Shukla. 2013. Shallow aquifer recharge from irrigation in a semiarid agricultural valley in New Mexico. *Journal of Hydrologic Engineering*, 18, 1219–1230.
- Ortiz, M., C. Brown, A.S. Fernald, T.T.R. Baker, B. Creel, and S. Guldán. 2007. Land use change impacts on acequia water resources in Northern New Mexico. *Journal of Contemporary Water Research & Education*, 137, 47–54.
- Ostrom, E. 1990. *Governing the commons: The evolution of institutions for collective action*. Cambridge, UK, and New York, NY: Cambridge University Press.
- Patton, M.Q. 2014. *Qualitative research and evaluation methods*, 4th ed. Los Angeles, CA: SAGE Publications, Inc.
- Pearce, T.M. 1980. *New Mexico place names: A geographical dictionary*. Albuquerque: University of New Mexico Press.
- Raish, C., and A.M. McSweeney. 2008. Land grants and the U.S. Forest Service. *Natural Resources Journal*, 48, 1039–1055.
- Reid, R.S., M.E. Fernández-Giménez, and K.A. Galvin. 2014. Dynamics and resilience of rangelands and pastoral peoples around the globe. *Annual Review of Environment and Resources*, 39, 217–242.
- Rivera, J.A. 1998. *Acequia culture: Water, land, and community in the Southwest*, 1st ed. Albuquerque: University of New Mexico Press.
- Roncoli, C., C. Jost, C. Perez, K. Moore, A. Ballo, S. Cissé, and K. Ouattara. 2007. Carbon sequestration from common property resources: Lessons from community-based sustainable pasture management in north-central Mali. *Agricultural Systems*, 94, 97–109.
- Schultz, E. 2013, January 29. Lawsuit against Forest Service moves forward. Retrieved June 14, 2018, from <https://lajicarita.wordpress.com/2013/01/29/lawsuit-against-forest-service-moves-forward/>
- Thornton, P.K., R.L. Kruska, N. Henninger, P.M. Kristjansson, R.S. Reid, and T.P. Robinson. 2003. Locating poor livestock keepers at the global level for research and development targeting. *Land Use Policy*, 20, 311–322.
- Tucker, J. 2012, November 30. Feds file motion to weaken ranchers' claim. Retrieved June 14, 2018, from <http://nmflc.blogspot.com/2012/11/feds-file-motion-to-weaken-ranchers.html>
- Turner, M.D. 2009. Capital on the move: The changing relation between livestock and labor in Mali, West Africa. *Geoforum*, 40, 746–755.
- Turner, M.D., J.G. McPeak, and A. Ayantunde. 2014. The role of livestock mobility in the livelihood strategies of rural peoples in semi-arid West Africa. *Human Ecology*, 42, 231–247.
- United States Government Accountability Office (U.S. GAO). 2001. Treaty of Guadalupe Hidalgo: Definition and list of community land grants in New Mexico [GAO-01-951]. Washington, D.C.: U.S. GAO.
- Walker, B., C.S. Holling, S.R. Carpenter, and A.P. Kinzig. 2004. Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society*, 9, 5.

# Perceptions of Drought Preparedness and Adaptation Strategies within Acequia Communities

Brian H. Hurd and Laura Mayagoitia

---

In Northern New Mexico, many small, rural communities are centered around small-scale irrigation systems, or *acequias*, that serve to meet local food and economic needs, nurture riparian flora and fauna, and connect communities with their environment. From 2002 to 2019, much of New Mexico experienced more years with drought than without drought. Although the weather is highly variable in Northern New Mexico, communities have endured and survived many previous episodes of drought. We conducted research, based on a survey administered in the autumn of 2011, that aimed to explore how *parciantes* (acequia member irrigators) perceive vulnerability and preparedness primarily in terms of the recent significant drought (and potential climate change), but also within the context of other concurrent challenges, including population growth, increased development, and the economic downturn that occurred just prior to this period in time. The survey further aimed to identify potential adaptation strategies and investments that can inform similar communities confronting related challenges.

Early economic research investigating the impacts and economic consequences of climate variability and change did not consider the potential role of adaptation (e.g., Revelle and Waggoner, 1983; Titus, 1992; Fankhauser, 1995; Waggoner, 1990; Watson et al., 1996). In general, these and other studies did not attempt to identify and incorporate specific changes in behavior, system management, or technology that might reduce or offset any adverse consequences from (or even take advantage of) altered physical and environmental changes stemming from a reaction to or anticipation of climate changes. Instead, these early studies looked at the effects of climate change on crop yields and overall production without trying to model changes in market prices and behavioral changes of farmers. The results of these studies often led to either under- or over-stating impacts and obscured a more complete understanding of the nature and process of behavioral change that underlies adaptation (Hurd, 2008a, 2008b).

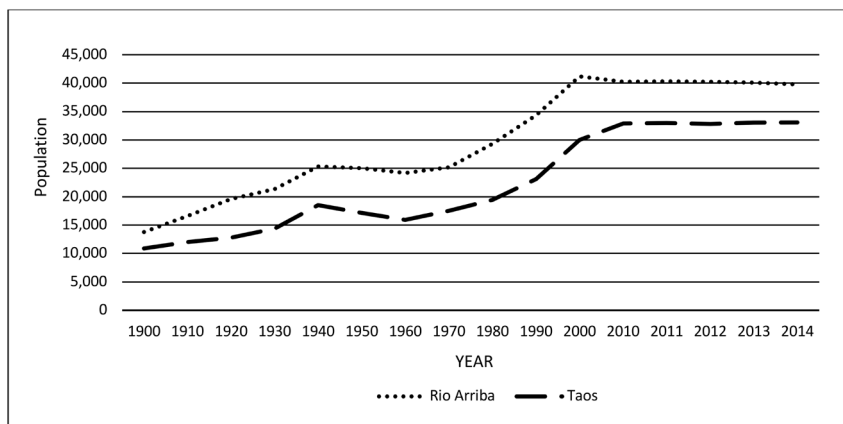
In this study, we attempted to identify the most important adaptive responses that irrigators are likely to consider when confronting significant drought and, to a lesser extent, other challenges, including regional population growth and economic downturn. In our survey, we chose the wording

of “significant drought”—the most likely expression of climate change that will be challenging the communities in Northern New Mexico—as a proxy for “climate change.” Irrigators will, of course, assess and balance the perceived benefits and costs associated with each particular adaptation on their own terms before deciding whether to implement them or not. It is precisely this uncertainty of the nature and extent of behavioral responses that previously challenged researchers—as noted above—in investigating the economic impacts of climate change. This study brought some clarity to this problem and to some of the behavioral issues regarding how significant drought is perceived, experienced, or anticipated, and it then identified which responses are plausible and appropriate.

## NORTHERN NEW MEXICO POPULATION AND ECONOMIC CONDITIONS AND TRENDS

Northern New Mexico’s Taos and Rio Arriba Counties are home to hundreds of the present-day acequia communities, including the communities we surveyed—Rio Hondo (Taos County), Alcalde-Velarde (Rio Arriba County), and El Rito (Rio Arriba County)—in 2011. Long-term economic trends show a steady transformation in these counties in regards to population, labor, and employment patterns. From about 1980 through the early 2000s, the population rose by nearly 40% in Rio Arriba County and 70% in Taos County as shown in Figure 1 (Economic Profile System, 2007, 2018). In addition, the 1990s were a period of rapid population growth and changing local demographics in many urban areas of New Mexico. The desirability of the Santa Fe region brought an influx not only to the city but also to the more affordable exurbs in and around the acequia communities (University of New Mexico Bureau of Business and Economic Research [UNM BBER], 2014).

Population increases generally create additional tensions on existing infrastructures, such as municipal services, regional transportation, and local utilities. Even in cases where domestic wells and septic systems meet household water and wastewater needs, the growing number of households results in increased pumping from local aquifers and heightened risks of septic failure and leakage into vulnerable waterways and aquifers. In addition, the infusion of



**Figure 1. Population growth trends of Rio Arriba and Taos Counties (UNM BBER, 2016).**

new people and faces—many without much knowledge or understanding of the region’s history and customs—has brought economic booms in both property values and development. However, this same influx of people has also brought challenges of acceptance, integration, and assimilation that have strained the fabric of acequia community customs and traditions of shared communal responsibilities (Francis, 2004). For example, many of the new or recent arrivals to New Mexico are unaccustomed to traditions such as the annual *la limpia de las acequias* (spring cleaning of the ditches in preparation for irrigation season). These residents tend to misunderstand the participatory nature of such communal obligations. The resulting diminution of social cohesion lessens the social bonds and communal attachment that often accompanies community perceptions of strength and resilience (Rodríguez, 2006). A further result is a possible weakening in communication networks and, for example, the sharing of drought adaptation strategies.

Along with population growth, the character of jobs and income both locally within acequia communities and across the region has changed. The last half century has witnessed a transition from resource-based jobs and incomes, such as timber, grazing, farming, and mining, into an economy more dependent on service jobs, including retail as well as professional and government services. For example, from the early 1970s through the early 2000s, the share of service jobs rose from about 50% to nearly 70% and from about 40% to over 50% in Taos and Rio Arriba Counties, respectively, and the shares of agricultural jobs remained relatively constant, with the share of jobs at approximately 4% and 8% for Taos and Rio Arriba, respectively (UNM BBER, 2014). The most recent statistics for population, jobs, and incomes, however, have mirrored the slowdown from the economic recession and slow recovery. How soon and to what extent a pattern of growth re-emerges remains uncertain (U.S. Bureau of Economic Analysis, n.d., 2019).

A related trend, one that perhaps renders some good news for the region’s communities, is that a diminished dependence on resource-based jobs and incomes comes at a time of possible climatic changes that are likely linked to increasing drought frequency, duration, and severity (Rupasingha and Patrick, 2010). Timber, grazing, and farming incomes are all highly dependent on rainfall and available irrigation water, and therefore diminished reliance on these sources provides greater capacity to cope with and manage drier weather conditions. The question remains, however, at what point do persistent and intense drought conditions, like those suggested by some climate change sce-

narios, push communities and the agro-environmental systems that surround them beyond their current capabilities and capacities to withstand and remain resilient in response to these stressors (Mayagoitia et al., 2012)?

## SURVEY METHODS AND APPROACH

**Objective.** During the summer of 2011, a survey of acequia parciales was conducted in the communities of Alcalde-Velarde, Rio Hondo, and El Rito, New Mexico. The aim was to gain insight and learn about parciales’ perceptions of their family’s and community’s vulnerability, preparedness, and most needed adaptation strategies and investments in order to cope with continuing significant drought as well as population growth, development pressure, and economic stress. For example, we hypothesized that the relative strength of perceived preparedness would contribute to a community’s collective resilience to adversity and may also indicate the community’s responsiveness and receptiveness to possible improvements and adaptations.

**Approach and methods.** We developed, pre-tested, and implemented a survey to measure, test, and compare member perceptions of family and community vulnerability, preparedness, adaptation possibilities, and needed investments in order to better cope with economic, drought, development, and demographic stresses. We surveyed 50 acequia parciales from the communities of Alcalde-Velarde, El Rito, and Rio Hondo using in-person interviews in early autumn of 2011.<sup>1</sup>

The several sections that follow describe some of the key findings and insights that emerged from our study, including perceptions regarding individual and community preparedness, specific adaptation strategies, and needed resources and investments that confer some measure of stability and resilience.

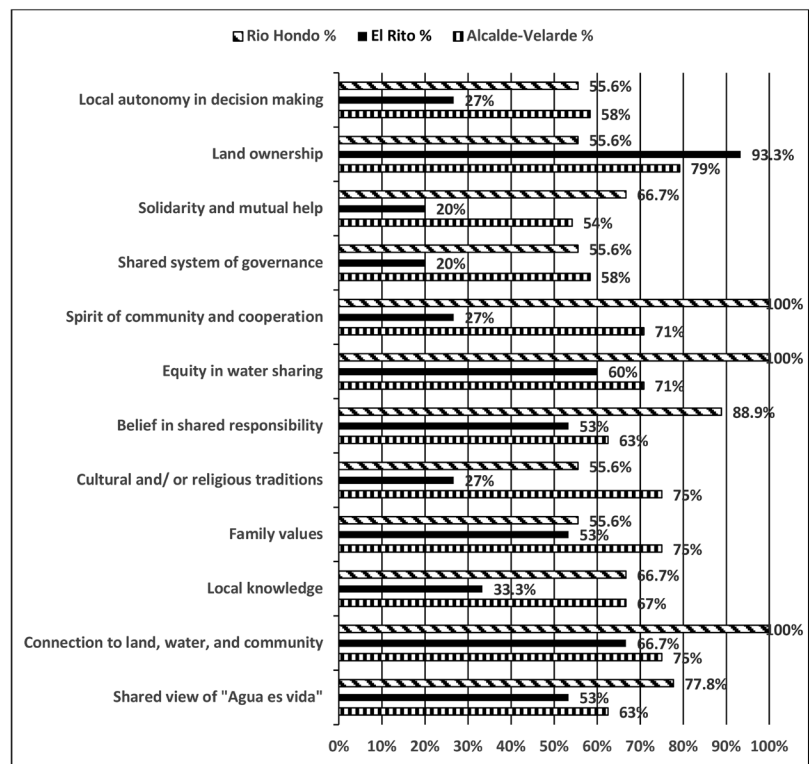
## Acequia community characteristics and their role in perceived preparedness and adaptive capacity

If and when adverse conditions emerge, households and communities generally strive to respond and react to the changing conditions. How well they do so, in many cases, depends on their level of general preparedness, knowledge and understanding of the changes, and their **adaptive capacity** (Brooks and Adger, 2005). The latter is a term that characterizes the flexibility, amount of available resources, and capability to adjust in a timely and effective fashion to some change or disturbance in, for example, economic conditions, population levels, and/or changes in the environment, such as water availability or drought (Lemos et al., 2007; Jones et al., 2010).

Acequia communities generally have a deep and long commitment to place, history, and culture (Rivera, 1996, 1998; Rodríguez, 2006). These communities demonstrate their character in the patterns of community governance, agricultural practices, and cultural traditions (Peña, 2005; Eastman et al., 1997). A key component of this study was to identify crucial factors influencing preparedness and adaptation capacity by asking parciales to choose from a list of characteristics that they perceived would contribute the most in preparing the community for significant drought and other challenges, such as economic downturns, population growth, and increased development. Parciales were asked to identify which of the following characteristics “you believe have helped you and your neighbors adapt to economic downturns, population growth, increased development, and droughts in the past.” We presented parciales with the following list of characteristics:

- 1) Local autonomy in decision making
- 2) Land ownership
- 3) Solidarity and mutual help
- 4) Shared system of governance
- 5) Spirit of community and cooperation
- 6) Equity in water sharing
- 7) Belief in shared responsibility
- 8) Cultural and/or religious traditions
- 9) Family values
- 10) Local knowledge
- 11) Connection to land, water, and community
- 12) Shared view of “*Agua es vida*” (e.g., feeling of collective identity and strength through connectedness of life to water)

We observed that members of the Rio Hondo acequia identified strength in several characteristics, with 100% of parciales exhibiting support for the role and value of a “spirit of



**Figure 2.** Acequia community characteristics that “best” contribute to community preparedness and adaptive capacity (% of parciales interviewed) (Mayagoitia, 2011; Mayagoitia et al., 2012).

community and cooperation,” a community sense of “equity in water sharing,” and “connection to land, water, and community.” A close fourth—89% of parciales—chose a “belief in shared responsibility.” Although Rio Hondo strongly associated with “connection to land, water, and community,” El Rito and Alcalde-Velarde acequia communities identified with this category at 67% and 75% of parciales, respectively. Parciales on the acequia of El Rito were strongly drawn to the characteristic of “land ownership” at 93% of parciales, followed by “connection to land, water, and community” (as stated above) and “equity in water sharing” at 60% of parciales. Notably at 79% of parciales, Alcalde-Velarde also identified with “land ownership” as its top characteristic. Surprisingly, fewer El Rito respondents identified strongly with “solidarity and mutual help” and a “shared system of governance”—both receiving only 20% of parciales compared with over 50% of parciales in the Rio Hondo and Alcalde-Velarde communities. In similar findings of low support, only 27% of El Rito parciales identified with both “spirit of community and cooperation” and with “cultural and/or religious traditions,” whereas support in Alcalde-Velarde exceeded 70% and 75% of parciales, respectively, and Rio Hondo at 100% and 56% of parciales, respectively. Results for each of the three acequia communities on traits that best contribute to community preparedness and adaptive capacity are shown in Figure 2.



## Perceptions of community preparedness to selected challenges

Preparedness and adaptive capacity are important attributes in mitigating vulnerability and risk from stressors, such as significant drought, population growth, and economic hardship (Brooks and Adger, 2005; Jones et al., 2010). A key step in identifying possible adaptation strategies that will most likely gain community support and become successfully implemented is to observe individual perceptions of community preparedness.

In this section of the survey, we asked parciales to rate their beliefs about relative community preparedness versus vulnerability to “significant drought,” “population change and growth,” “regional and local economic downturn,” and “regional economic development pressure.” To each of these challenges there were significant numbers of respondents on both sides of the scale, i.e., “somewhat prepared” or “very prepared” and “somewhat vulnerable” or “very vulnerable.” Perceived vulnerability was highest for both “significant drought” at 42% of surveyed parciales and “regional economic development pressure” at 43%, where respondents indicated being “somewhat vulnerable” or “very vulnerable.” See Table 1 for more information.

Perceptions of community preparedness for “population change and growth” also varied across acequias from “very prepared” to “somewhat vulnerable,” with 32% of surveyed parciales holding a neutral opinion. Those in the Rio Hondo area found that recent patterns of “population change and growth” have not been too disruptive to community cohesion, with more than 55% indicating that the community was either “somewhat prepared” or “very prepared” and none indicating any level of “vulnerability.” In contrast, 43% of parciales in El Rito and 38% of parciales in Alcalde-Velarde felt the communities were “somewhat vulnerable” to the stresses of “population change and growth.” Results are shown in Table 1 and summarized across all three acequias in Figure 3.

## Assessment of the effectiveness of potential adaptation strategies

Whether the result of weather variability or climatic change, acequia communities are vulnerable to diminished streamflow and water availability that accompanies significant and prolonged periods of drought (Gutzler, 2007; D’Antonio, 2006). Reduced streamflow and altered runoff patterns present challenges to the rhythms of the community, irrigators, local food supplies, and incomes (Hurd and Coonrod, 2012). Acequia communities have long struggled with and endured through periodic droughts by developing effective water sharing agreements (*repartimientos*). These agreements generally aim to provide for equitable water allocations (under both abundance and shortage) that are typically based on established patterns of use and are usually in proportion to irrigated land areas. Specific customs

**Table 1. Parciales’ Perceived Community Preparedness Versus Vulnerability to Selected Challenges (% of parciales interviewed) (Mayagoitia, 2011; Mayagoitia et al., 2012)**

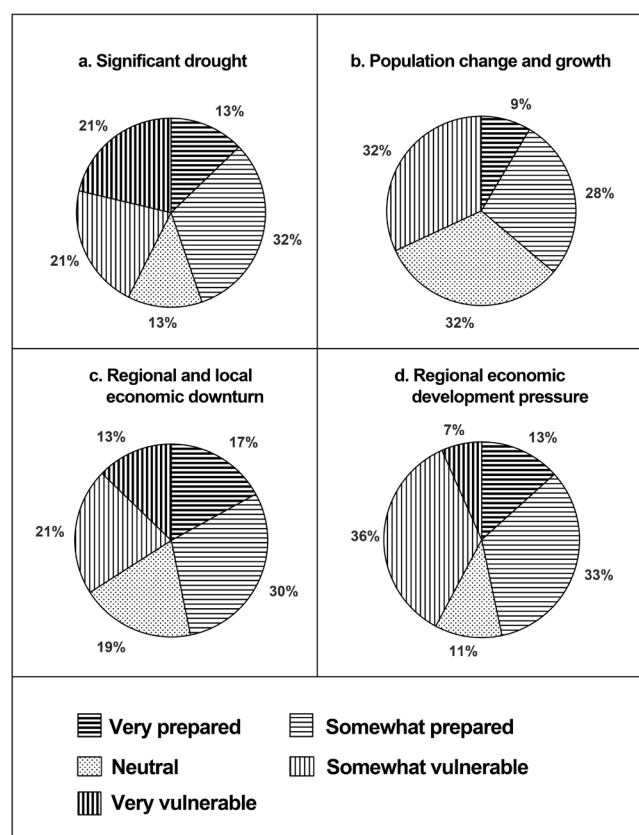
Activity	Acequia regions			
	Alcalde-Velarde	El Rito	Rio Hondo	Overall*
<b>Significant drought</b>				
Very prepared	17	7.1	11.1	13
Somewhat prepared	21	35.7	55.6	32
Neutral	17	7.1	11.1	13
Somewhat vulnerable	29	7.1	22.2	21
Very vulnerable	17	42.9	-	21
<b>Population change and growth</b>				
Very prepared	8	7.1	11.1	9
Somewhat prepared	25	21.4	44.4	28
Neutral	29	29	44.4	32
Somewhat vulnerable	38	42.9	-	32
Very vulnerable	-	-	-	-
<b>Regional and local economic downturn</b>				
Very prepared	21	-	33.3	17
Somewhat prepared	25	28.6	44.4	29.8
Neutral	21	14.3	22.2	19.1
Somewhat vulnerable	25	28.6	-	21.3
Very vulnerable	8	28.6	-	13.0
<b>Regional economic development pressure</b>				
Very prepared	21	-	12.5	13
Somewhat prepared	21	53.8	37.5	33
Neutral	13	15.4	-	11
Somewhat vulnerable	38	30.8	37.5	36
Very vulnerable	8	-	12.5	7
<b>Response rate:</b>	<b>68%</b>	<b>27%</b>	<b>17%</b>	<b>34%</b>
<b>Sample size:</b>	<b>25</b>	<b>16</b>	<b>9</b>	<b>50</b>
* Reported percentages are acequia-specific. The “Overall” column is based on total sample				

may vary between acequias, with each community tailoring approaches to best meet the needs and physical and geographic characteristics of its watershed and irrigated lands (Rodríguez, 2006).

In addition to repartimientos and other traditional adaptation strategies, our research showed that acequia members have clear needs for more methods and approaches to soften the hardships during significant droughts. The survey presented several plausible adaptation strategies and asked parciales to indicate their opinion on whether or not the approach would contribute to their ability to cope with significant drought and water shortage.<sup>4</sup> Parciales rated their beliefs about the effects of potential adaptation strategies as positive versus negative in terms of “decrease planted area and fallow,” “switch some acres or parcels to dryland farming,” “plant higher yield cash crops on fewer acres,” “plant native or heirloom crops on some acres,” “reduce livestock numbers,” “consider alternative irrigation technology,” “improve soil to reduce evaporation,” and “use cold frames to start seedlings or plants.” The most frequently identified strategy was “improve soil to reduce evaporation,” which was chosen by more than 78% of surveyed parciales as either “very positive” or “positive.” The next most favored approach was “consider alternative irrigation technology” where 67% of surveyed parciales selected either “very positive” or “positive.” The third most promising approach, identified by 55% of surveyed parciales, was “use cold frames...” to jump start spring plant growth and make better use of early period runoff. Figure 4, which demonstrates the average across all acequias, and Table 2, which provides acequia-specific findings, show the opinions for various changes in practices in order to adapt to and cope with significant droughts and water scarcity.

### Perceived areas of needed resources and investments

We found that identifying adaptation strategies and other community actions that improve adaptation capacity is central to strengthening community resilience. In acequia communities, both private and public financial resources are often very limited, and therefore the emphasis is best placed on identifying the most cost-effective and welcomed activities and programs that can contribute to a community’s adaptive capacity. We addressed this issue by presenting respondents with a set of plausible steps, actions, or activities. We then asked them to rate how “helpful” it would be to dedicate more resources and attention to each activity in order to strengthen acequia community preparedness and ability to withstand challenges from economic hardships, population growth, development pressure, and significant droughts.<sup>5</sup> We presented nine possible programs, policies, and investments that could help strengthen adaptive capacity throughout the community and their families and asked participants to rate these from “very helpful” to “not at all helpful.” Categories included “data and informa-



**Figure 3. Parciales’ perceptions of community preparedness versus vulnerability to selected challenges, averaged across all acequias (% of parciales interviewed) (Mayagoitia, 2011; Mayagoitia et al., 2012).**

tion access and training,” “identify useful traditional techniques,” “increase public awareness of acequia traditions,” “provide training, education, and demonstrations,” “use of improved irrigation technology,” “legal training,” “better streamflow data,” “use of small-scale storage,” and “create local disaster-relief funds.”

Figure 5 and Table 3 show the findings across each activity. As indicated in Figure 5, on average the three activities with the greatest potential to be “helpful” (“very” and “somewhat”) were “increase public awareness of acequia traditions” (panel c), “identify useful traditional techniques” (panel b), and “provide hands-on-training, education, and practical demonstrations” (panel d), which received support from 96%, 91%, and 91% of parciales, respectively. Significant support—89% of surveyed parciales—was indicated for “legal training” (panel f). “Data and information access and training” (panel a) and “better streamflow data” (panel g) were fifth and sixth in being perceived as most helpful, followed closely by “use of improved irrigation technology” (panel e). Strong support, therefore, was given for continued efforts at collecting, maintaining, and disseminating data and information about irrigation technology and management. These findings

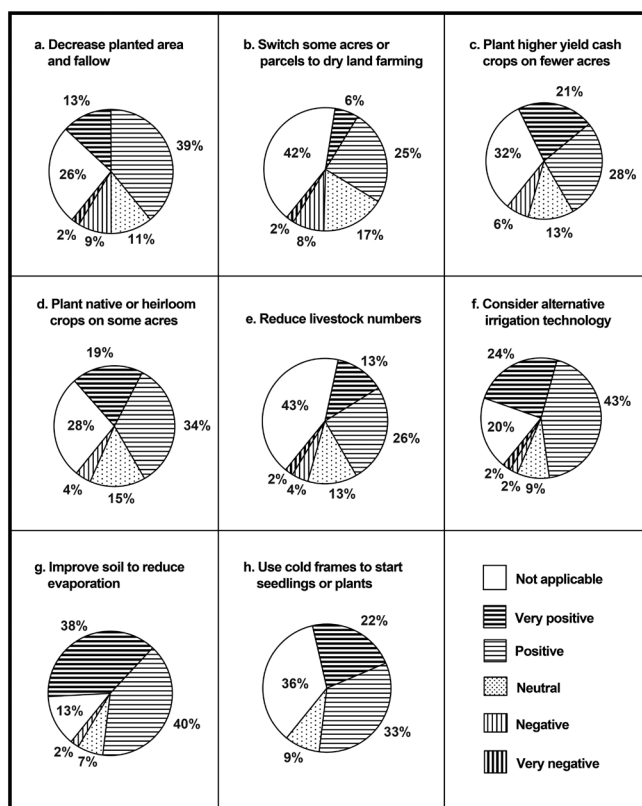
Table 2. Parciantes' Assessment of Potential Drought Adaptation Strategies (% of parciantes interviewed) (Mayagoitia, 2011; Mayagoitia et al., 2012)				
	Acequia regions			
Activity	Alcalde-Velarde	El Rito	Rio Hondo	Overall*
Decrease planted area and fallow				
Not applicable	20.8	28.6	37.5	26.1
Positive/ Very positive	62.5	35.7	50.0	52.2
Neutral	12.5	14.3	-	10.9
Negative/ Very negative	4.2	21.4	12.5	10.9
Switch some acres or parcels to dryland farming				
Not applicable	56.0	35.7	11.1	41.7
Positive/ Very positive	24.0	35.7	44.4	31.3
Neutral	12.0	7.1	44.4	16.7
Negative/ Very negative	8.0	21.4	-	10.4
Plant higher yield cash crops on fewer acres				
Not applicable	36.0	35.7	12.5	31.9
Positive/ Very positive	52.0	50.0	37.5	48.9
Neutral	12.0	14.3	12.5	12.8
Negative/ Very negative	-	-	37.5	6.4
Plant native or heirloom crops on some acres				
Not applicable	32.0	28.6	12.5	27.7
Positive/ Very positive	56.0	50.0	50.0	53.2
Neutral	12.0	14.3	25.0	14.9
Negative/ Very negative	-	7.1	12.5	4.3

Reduce livestock numbers				
Not applicable	52.0	35.7	25.0	42.6
Positive/ Very positive	32.0	42.9	50.0	38.3
Neutral	16.0	-	25.0	12.8
Negative/ Very negative	-	21.4	-	6.4
Consider alternative irrigation technology				
Not applicable	16.7	30.8	11.1	19.6
Positive/ Very positive	62.5	61.5	88.9	67.4
Neutral	12.5	7.7	-	8.7
Negative/ Very negative	8.3	-	-	4.3
Improve soil to reduce evaporation				
Not applicable	8.3	30.8	-	13.3
Positive/ Very positive	83.3	61.5	87.5	77.8
Neutral	8.3	7.7	-	6.7
Negative/ Very negative	-	-	12.5	2.2
Use cold frames to start seedlings or plants				
Not applicable	32	54	14	36
Positive/ Very positive	60	31	86	55
Neutral	8	15	-	9%
Negative/ Very negative	-	-	-	-
<b>Response rate:</b>	<b>68%</b>	<b>27%</b>	<b>17%</b>	<b>34%</b>
<b>Sample size:</b>	<b>25</b>	<b>16</b>	<b>9</b>	<b>50</b>
* Reported percentages are acequia-specific. The "Overall" column is based on total sample.				

Table 3. Parciantes' Perceived Areas of Needed Resources and Investments (% of parciantes interviewed) (Mayagoitia, 2011; Mayagoitia et al., 2012)				
	Acequia regions			
Activity	Alcalde-Velarde	El Rito	Rio Hondo	Overall*
Data and information access and training				
No response				6
Not at all helpful	13	8	-	9
Somewhat helpful	13	67	44.4	32
Very helpful	74	25	55.6	53
Identify useful traditional techniques				
No response				6
Not at all helpful	4	-	-	2
Somewhat helpful	13	42	11.1	19
Very helpful	78	75	77.8	72
Increase public awareness of acequia traditions				
No response				4
Not at all helpful	-	-	-	0
Somewhat helpful	9	42	11.1	17
Very helpful	91	75	77.8	79
Provide training, education, and demonstrations				
No response				4
Not at all helpful	9	-	-	4
Somewhat helpful	4	50	44.4	23
Very helpful	87	58	55.6	68
Use of improved irrigation technology				
No response				6
Not at all helpful	9	25	-	10
Somewhat helpful	30	42	44.4	33
Very helpful	65	42	44.4	50

Legal training				
No response				4
Not at all helpful	9	8	-	6
Somewhat helpful	13	50	22.2	23
Very helpful	78	50	77.8	66
Better streamflow data				
No response				2
Not at all helpful	9	33	-	13
Somewhat helpful	22	17	33.3	21
Very helpful	70	67	66.7	64
Use of small-scale storage				
No response				4
Not at all helpful	17	17	11.1	15
Somewhat helpful	13	33	11.1	17
Very helpful	74	58	77.8	65
Create local disaster-relief funds				
No response				13
Not at all helpful	13	25	11.1	15
Somewhat helpful	17	8	22.2	15
Very helpful	65	58	55.6	57
<b>Response rate:</b>	<b>68%</b>	<b>27%</b>	<b>17%</b>	<b>34%</b>
<b>Sample size:</b>	<b>25</b>	<b>16</b>	<b>9</b>	<b>50</b>
* Reported percentages are acequia-specific. The "Overall" column is based on total sample.				



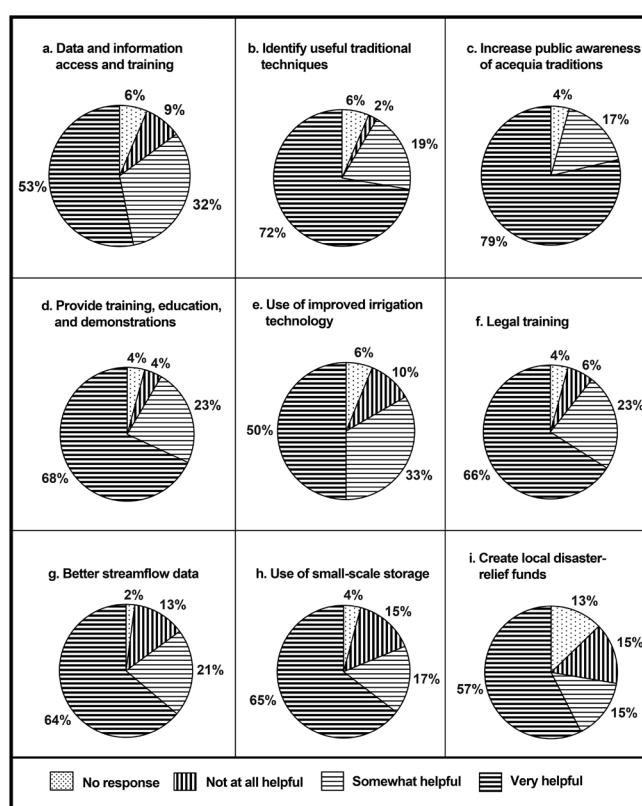


**Figure 4.** Parciantes' perceptions of the effectiveness of possible drought adaptation strategies, averaged across all acequias (% of parciantes interviewed) (Mayagoitia, 2011).

show that the highest priorities were given to the cultural identity of acequia communities and to the need for continued learning and training on the techniques of crop production, water use, and legal aspects of land and water in New Mexico.

## CONCLUSIONS

Acequia communities continue to react and adjust to the stresses of economic, population, development, and environmental challenges. Our research suggests perceived vulnerabilities are significant; for example, nearly 42% of surveyed parciantes perceived some vulnerability ("very vulnerable" and "somewhat vulnerable") to significant drought, and that preparedness and adaptive capacity can be improved. Some mitigation of social and economic stress has come with greater regional economic development and diversification. For example, as acequia communities transition toward more non-agricultural sources of income, they develop opportunities for additional economic connections to the broader region (Fernald et al., 2015). Drought and other factors that reduce or limit water supply or access can have adverse consequences on acequia communities. However, the findings suggested that there are several po-



**Figure 5.** Parciantes' perceptions of areas of needed resources and investments, averaged across all acequias (Mayagoitia, 2011).

tentially effective adaptation strategies at both individual and community levels (shown in Table 2) that can further strengthen adaptive capacity and build economic and social resilience. Key among them (with selected percentages in parentheses) are:

1. Improve soil to reduce evaporation (78% of parciantes)
2. Consider alternative irrigation technology (67% of parciantes)
3. Use cold frames to start seedling growth (55% of parciantes)
4. Plant native or heirloom crops on some acres (53% of parciantes)
5. Decrease planted area and fallow (52% of parciantes)
6. Plant higher yield cash crops on fewer acres (49% of parciantes)

The capacity for these communities to leverage local customs, institutions, and knowledge with the potential of new techniques and methods could harness truly effective adaptation strategies. Findings also provide preliminary support for activities aimed at community strengthening and cooperation building within and between communities.

In particular, there is support for strengthening rural Extension programs and activities aimed at providing training, education, and demonstrations of new techniques and methods and how they can best integrate within existing community cultural systems. These would also include hands-on workshops and individualized training, which are important conduits for communication, information dissemination, and eventual adoption by acequia member irrigators.

## ENDNOTES

1. The study is fully described in Ms. Mayagoitia's master's thesis (Mayagoitia, 2011); a summarized version is found in Mayagoitia et al. (2012).
2. Survey question 23: "From the list below, circle the characteristics of your acequia that you believe have helped you and your neighbors adapt to economic downturns, population growth, increased development, and droughts in the past. Circle as many choices as you would like that apply to your acequia community. (Circle all that apply)."
3. Survey question 24: "There are many challenges facing acequia communities and *parciantes*. Please carefully read each of the challenges bolded and described in the Table below, and next to each one circle the response that best fits you and your community."
4. Survey question 12: "If a drought is expected, some farmers try to change crops and other practices to help provide some income even with water shortages. Some of the possible changes in activities and practices that could be helpful during periods of drought or water shortage are listed below. For those applicable to your farm or ranch, please indicate your opinion on the effect you believe it would have on your ability to cope with drought and water shortages."
5. Survey question 25: "In this final question, we would like to learn about possible steps, actions and activities that you think would be most HELPFUL in strengthening the ability of your acequia community to withstand the challenges described in the previous question. Consider the actions and activities in the Table below, and for each one please indicate how helpful it would be to have more attention and resources for that activity in order to better prepare your acequia in confronting the challenges of economic downturns, population growth, increased development, and drought."

## ACKNOWLEDGMENTS

We would like to express our gratitude to the acequia *parciantes* who participated in our study. Also, we are grateful for the guidance and support of Paula Garcia and Quita Ortiz and the New Mexico Acequia Association in preparing study materials. Without our terrific and supportive colleagues and the institutional support from the New Mexico Water Resources Research Institute and its director, Sam Fernald, this research would not have been successful. We

are also grateful for the continuing support of New Mexico State University and its Agricultural Experiment Stations. Finally, we are grateful to USDA's National Institute for Food and Agriculture (NIFA) for continued financial support under the Hatch Funded project, "A Coupled-Model Approach to Water Systems and Resource Impact Assessment" (#226443).

## REFERENCES

- Brooks, N., and W.N. Adger. 2005. Assessing and enhancing adaptive capacity. United Nations Framework Convention on Climate Change. Retrieved February 24, 2019, from <https://www4.unfccc.int/sites/NAPC/Country%20Documents/General/apf%20technical%20paper07.pdf>
- D'Antonio, J.R. 2006. The impact of climate change on New Mexico's water supply and ability to manage water resources. New Mexico Office of the State Engineer/ Interstate Stream Commission. Retrieved February 26, 2020, from <https://cdm16256.contentdm.oclc.org/digital/collection/p267801coll5/id/825>
- Eastman, C., J.P. King, and N.A. Meadows, 1997. Acequias, small farms, and the good life. *The Journal of Culture and Agriculture*, 19, 14–23.
- Economic Profile System. 2007. A socioeconomic profile: Rio Arriba County, New Mexico. Retrieved September 28, 2016, from [https://headwaterseconomics.org/wp-content/uploads/santafe-EPS-p\\_Rio\\_Arriba\\_County\\_New\\_Mexico.pdf](https://headwaterseconomics.org/wp-content/uploads/santafe-EPS-p_Rio_Arriba_County_New_Mexico.pdf)
- Economic Profile System. 2018. A socioeconomic profile: Taos County, New Mexico. Retrieved September 28, 2016, from [https://headwaterseconomics.org/wp-content/uploads/Taos\\_County\\_Economy.pdf](https://headwaterseconomics.org/wp-content/uploads/Taos_County_Economy.pdf)
- Fankhauser, S. 1995. *Valuing climate change: The economics of the greenhouse*. London: Routledge.
- Fernald, A., S. Guldán, K. Boykin, A. Cibils, M. Gonzales, B. Hurd, S. Lopez, C. Ochoa, M. Ortiz, J. Rivera, S. Rodriguez, and C. Steele. 2015. Linked hydrologic and social systems that support resilience of traditional irrigation communities. *Hydrology and Earth System Sciences*, 19, 293–307.
- Francis, K. 2004. Unearthing the acequias: A Penny White proposal. Retrieved September 28, 2016, from [http://www.nmacequiacommission.state.nm.us/Publications/kfrancis\\_harvard\\_proposal04.pdf](http://www.nmacequiacommission.state.nm.us/Publications/kfrancis_harvard_proposal04.pdf)
- Gutzler, D. 2007. *Climate change and water resources in New Mexico/New Mexico earth matters*. Albuquerque, NM: New Mexico Bureau of Geology and Mineral Resources.
- Hurd, B. 2007. Challenges of adapting to a changing climate. *UCLA Journal of Environmental Law and Policy*, 25, 77–92.
- Hurd, B. 2008. Coping and adapting to a changing climate: Concepts, issues and challenges. *Annals of Arid Zone*, 47, 221–231.

- Hurd, B.H., and J. Coonrod. 2012. Hydro-economic consequences of climate change in the Upper Rio Grande. *Climate Research*, 53, 103–18.
- Jones, L., E. Ludi, and S. Levine. 2010. Towards a characterization of adaptive capacity: A framework for analyzing adaptive capacity at local level. Retrieved September 28, 2016, from <https://www.odi.org/publications/5177-towards-characterisation-adaptive-capacity-framework-analysing-adaptive-capacity-local-level>
- Lemos, M.C., E. Boyd, E.L. Tompkins, H. Osbahr, and D. Liverman. 2007. Developing adaptation and adapting development. *Ecology and Society*, 12(2).
- Mayagoitia, L. 2011. *Adapting water, economy, and values in small community irrigation (acequia) systems to the challenges of regional growth and climate change* [master's thesis]. Las Cruces: New Mexico State University.
- Mayagoitia, L., B. Hurd, J. Rivera, and S. Guldán. 2012. Rural community perspectives on preparedness and adaptation to climate-change and demographic pressure. *Journal of Contemporary Water Research & Education*, 147, 49–62.
- Peña, D.G. 2005. *Mexican Americans and the environment: Tierra y vida*. Tucson: University of Arizona Press.
- Revelle, R.R., and P.E. Waggoner. 1983. Effects of a carbon dioxide-induced climatic change on water supplies in the western United States. In *Changing climate: Report of the carbon dioxide assessment committee* (pp. 419–431).
- Rivera, J.A. 1996. Irrigation communities of the Upper Rio Grande bioregion: Sustainable resource use in the global context. *Natural Resources Journal*, 36, 731–760.
- Rivera, J.A. 1998. *Acequia culture: Water, land, and community in the Southwest*. Albuquerque: University of New Mexico Press.
- Rodríguez, S. 2006. *Acequia: Water-sharing, sanctity, and place*. Santa Fe, NM: School for Advanced Research Press.
- Rupasingha, A., and J.M. Patrick. 2010. Rural New Mexico economic conditions and trends [Circular 651]. Las Cruces: New Mexico State University Cooperative Extension Service.
- Titus, J.G. 1992. The costs of climate change to the United States. In S.K. Majumdar, L.S. Kalkstein, B. Yarnal, E.W. Miller, and L.M. Rosenfeld (Eds.), *Global climate change: Implications, challenges and mitigation measures* (pp. 384–409).
- University of New Mexico Bureau of Business and Economic Research (UNM BBER). 2014. Population estimates and forecasts for: Growth management areas, sustainable development areas, and the water/wastewater service area county of Santa Fe 1990–2030 geospatial and population studies, Retrieved Feb 23, 2017, from <http://www.santafecountynm.gov/userfiles/SantaFePopulationGrowthReport.pdf>
- University of New Mexico Bureau of Business and Economic Research (UNM BBER). 2016. State and county population estimates. Retrieved Oct. 21, 2016, from <http://bber.unm.edu/data>
- U.S. Bureau of Economic Analysis. n.d. Regional data: GDP and personal income. Retrieved February 26, 2020, from <https://apps.bea.gov/itable/itable.cfm?ReqID=70&step=1>
- U.S. Bureau of Economic Analysis. 2019. Employment by county, metro, and other areas. February 26, 2020, from <https://www.bea.gov/data/employment/employment-county-metro-and-other-areas>
- Waggoner, P.E. (Ed.). 1990. *Climate change and US water resources*. New York: Wiley-Interscience.
- Watson, R.T., M.C. Zinyowera, and R.H. Moss, 1996. Climate change 1995: Impacts, adaptations and mitigation of climate change—Scientific-technical analyses. *Environment and Development Economics*, 2, 223–229.

# Connection and Integration: A Systems Approach to Exploring Acequia Community Resiliency

Ben L. Turner and Vincent C. Tidwell

---

## INTRODUCTION

*Acequia* irrigation communities are unique systems of people, land, water, and culture that have persisted for centuries. In the preceding chapters, the book's coauthors have described various features or components of these unique acequia systems in some detail. However, knowledge regarding potential future conditions, the risks they pose to acequias, and subsequent identification of appropriate adaptive strategies aren't always easily recognizable from a single disciplinary perspective. Therefore, an interdisciplinary approach that integrates key concepts and relationships across the entire system can be of great value in identifying system vulnerabilities and adaptive strategies. In this chapter, we will describe the efforts made to quantitatively integrate the various components and connections of an acequia system using the interdisciplinary approach called **system dynamics**.

We chose system dynamics (SD), a methodology for studying complex systems, as a unifying framework for several reasons. First, SD provides an intuitive and informative way to display the multifaceted connections operating within complex systems. Secondly, the SD method places priority on decision-making processes and mental models of stakeholders (personal values, beliefs, norms, and "filters" by which we interpret the world around us), both of which are important for understanding a system's behavior over time (Senge, 1990). Lastly, the SD process ends with the completion of a quantitative model (based on the connections and decision-making processes identified in the prior steps) capable of testing hypotheses that aren't easily addressed by models within a single disciplinary (reductionist) framework. Due to the important role of community leaders and *parciantes*, the traditional ways that the irrigation ditches are managed throughout the year, and the importance of the agricultural and hydrological processes that are affected, the SD method was well suited to capture both the qualitative and quantitative aspects of the acequia system. (For detailed descriptions of the SD process, see Senge [1990] for qualitative characteristics, Sterman [2000] for quantitative methodology, or Turner et al. [2016a] for applications to agriculture and natural resource management problems.)

The purpose of this chapter is to describe a model of acequia operations and then test the model under different future conditions. We will begin this description with an introduction to SD by providing a brief orientation to the systems thinking process that was employed to draw connections between components or sub-sectors within the acequia SD model. Then we will describe each one of these acequia sub-sectors, its key dynamic behaviors, and the connections between the different acequia functions across disciplinary boundaries. To show these connections, we will use **causal loop diagrams** (CLD), a visual schematic or map of the systemic connections between variables, to illustrate the complex feedback processes that are at work between the natural system components and the various stakeholders operating in an acequia community. We will then briefly provide an overview of the quantitative model. Lastly, we will test the model to explore possible future responses of acequia community systems to different challenges or threats (e.g., climate or economic conditions) based on alternative trajectories of the past, a method of learning that has been employed for similar hydrologic and community systems facing similar threats as acequias (Srinivasan, 2015). For ease of interpretation, quotations will be used around the CLD components when the behavior is referenced and relates to their associated figure. If the component is discussed in general terms, quotations will not be used. In addition, not all of the possible feedbacks and interactions will be illustrated.

## SYSTEM DYNAMICS ACEQUIA MODEL

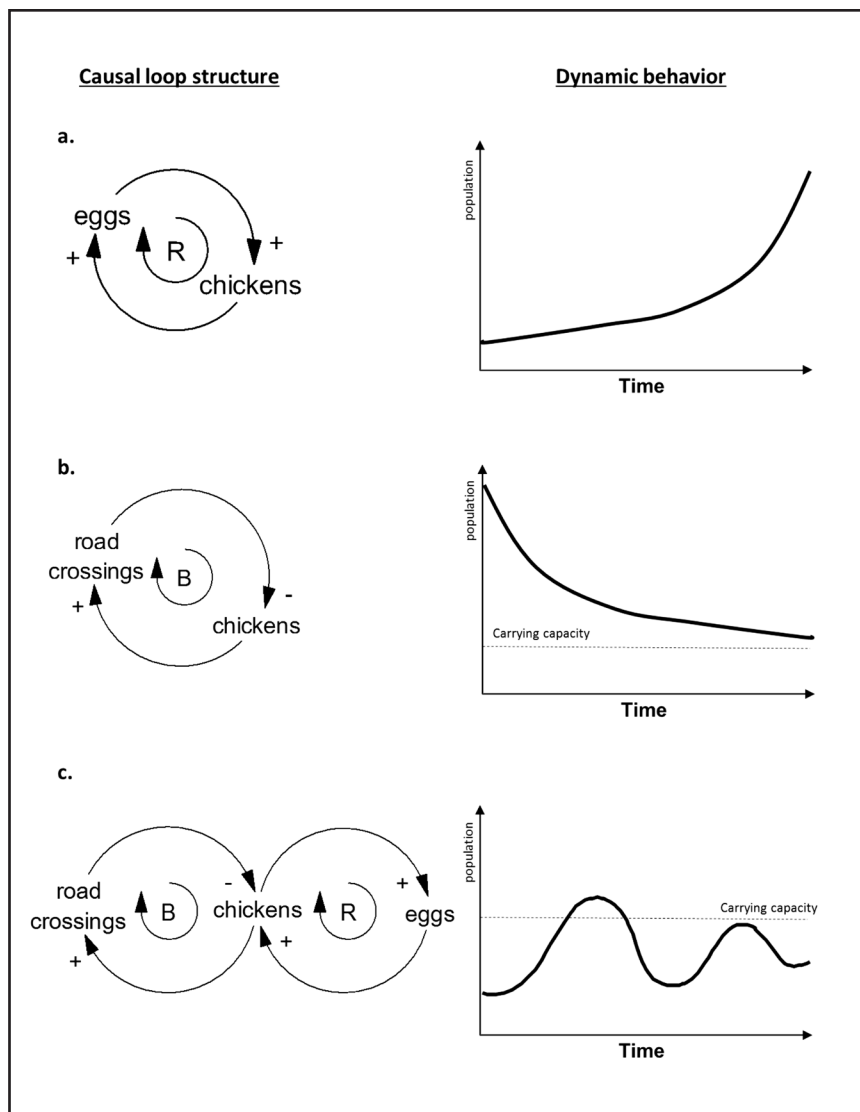
### Orientation to the symbols used in system dynamics

The first step in developing a system dynamics model (or any type of model) is the creation of a conceptual model, that is, a mapping of the key interactions occurring within the system being simulated (e.g., rainfall causally impacts runoff). One means of organizing and displaying a conceptual model is through the use of a causal loop diagram. Central to the CLD is the identification of **feedback loops**



that either create growth (or decay) or act to self-correct the behavior of a system (Sterman, 2000). Visually, feedback loops are created using **causal links**, specified with a “+” or “-” sign depending on the cause-and-effect relationship (Figure 1). When the causal relationships create unencumbered growth or decay, the loop is called a **reinforcing (or positive) feedback process** (Figure 1a). For the example shown, increasing “egg” levels will lead to a greater number of “chickens,” leading to still more “eggs” (Figure 1a). The arrows represent causal relationships between two variables. The “+” signs indicate that the effect is positively related to the cause (i.e., if “eggs” increase, “chickens” increase). The loop is therefore self-reinforcing, identified with the “R” symbol inside the loop.

When the causal relationships self-correct one another such that growth or decay is hindered or offset by another force, the feedback is called a **balancing (or negative) feedback process**. Negative loops counteract change in a system. As the “chicken population” rises, various negative loops will act to balance the “population” with its “carrying capacity.” The more “chickens,” the more “road crossings” that will be attempted. With more “road crossings” there will be fewer “chickens” (indicated by the “-” sign on the link). Because the negative feedback balances the “chicken population” nearer to its capacity, the loop is denoted inside with a “B” (Figure 1b). Coupled together, positive feedback creates growth (i.e., more “chickens”), which is self-corrected through more “road crossings” (fewer “chickens”), creating a fluctuating dynamic behavior (Figure 1c). Balancing and reinforcing loops can be combined in numerous ways within CLDs. In the sections that follow, various sub-sectors of an acequia system will be presented in their own CLD with a description of the dynamic behavior that they account for in the SD model. Each section that follows, including its respective CLD, has been simplified to highlight the core feedbacks within that particular acequia component. For complete descriptions of the model variables, feedbacks, and interactions, we recommend Turner et al. (2016b) and Gunda et al. (2018).



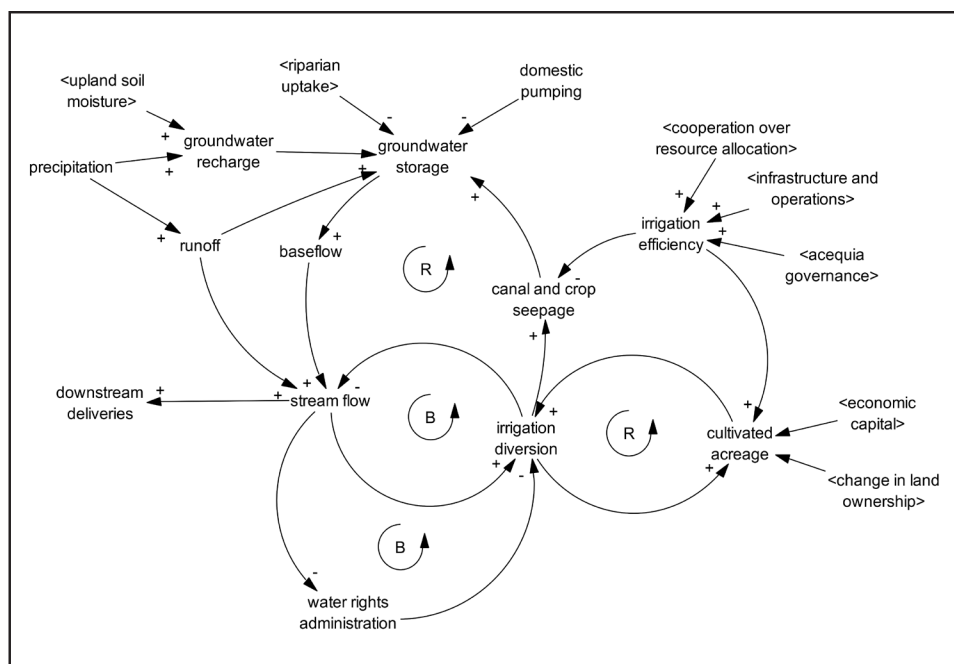
**Figure 1.** Types of feedback processes (positive and negative) with their causal loop structure and an illustration of the dynamic behavior over time produced by the causal structure (adapted from Sterman [2000]).

## Hydrology

The hydrology CLD connects the three principal water stocks: “streamflow,” “groundwater storage,” and “irrigation diversions” (Figure 2). Surface water runoff (noted as “runoff”) and shallow groundwater **baseflow** (noted as “baseflow”) drive surface water streamflow (noted as “streamflow”). The primary source of these flows is “precipitation” (both rainfall and snowfall); however, “upland soil moisture” may also contribute to “groundwater recharge” and therefore “runoff” and “baseflow.” We include “upland soil moisture” in order to account for important hydrologic linkages between acequia valleys and upland management decisions, such as forest management and livestock grazing. “Streamflow” is then allocated into two

components: “irrigation diversion” to the acequias or to other users and “downstream deliveries.” Because of the unique management structure of acequias who collectively manage irrigation based on annual streamflow conditions, we included a factor for “water rights administration” that regulates the rate of “irrigation diversions” depending on the available streamflow. Once in the acequia ditch itself, water is partitioned to crop uptake (which links through to the “cultivated acreage” that reinforces demand for water), “canal and crop seepage,” and “runoff” that re-enters the “streamflow.” “Canal and crop seepage” contribute to recharging the shallow groundwater storage (noted as “groundwater storage”) but may be reduced due to enhanced “irrigation efficiency,” which facilitates greater **consumptive use** of water during cultivation. “Groundwater storage” may be further reduced from “riparian uptake” and “domestic pumping.” Additional linkages with other acequia components, such as economics and land use, governance and cooperation, or infrastructure, may also influence the local hydrology through the effects they have on irrigation demand for “cultivated acreage” and the overall “irrigation efficiency” of the system.

Due to their connectivity to other components of the acequia system, two important potential **leverage points**, or places in a system’s structure where a small change can lead to significant and lasting results, are to note: “water rights administration” (the policies and practices used to allocate surface water flows) and “irrigation diversions” (which influence the economic benefits to parciantes through cultivated acreage and the ecological benefits through seepage and groundwater recharge). For example, acequia systems are linked to various ecological, economic, and sociocultural aspects, including wetland and **riparian habitats**, and land ownership. Land ownership drives land use decisions that influence crop, forage, and livestock production as well as irrigation and domestic pumping (Fernald et al., 2001; Ocampo et al., 2006; Arumi et al., 2009; Jencso et al., 2009; Fernald et al., 2010). Maintenance of the acequia conveyance system supports the provision of critical **ecosystem services** and the benefits people obtain from ecosystems (e.g., reduced peak flows, migration cor-



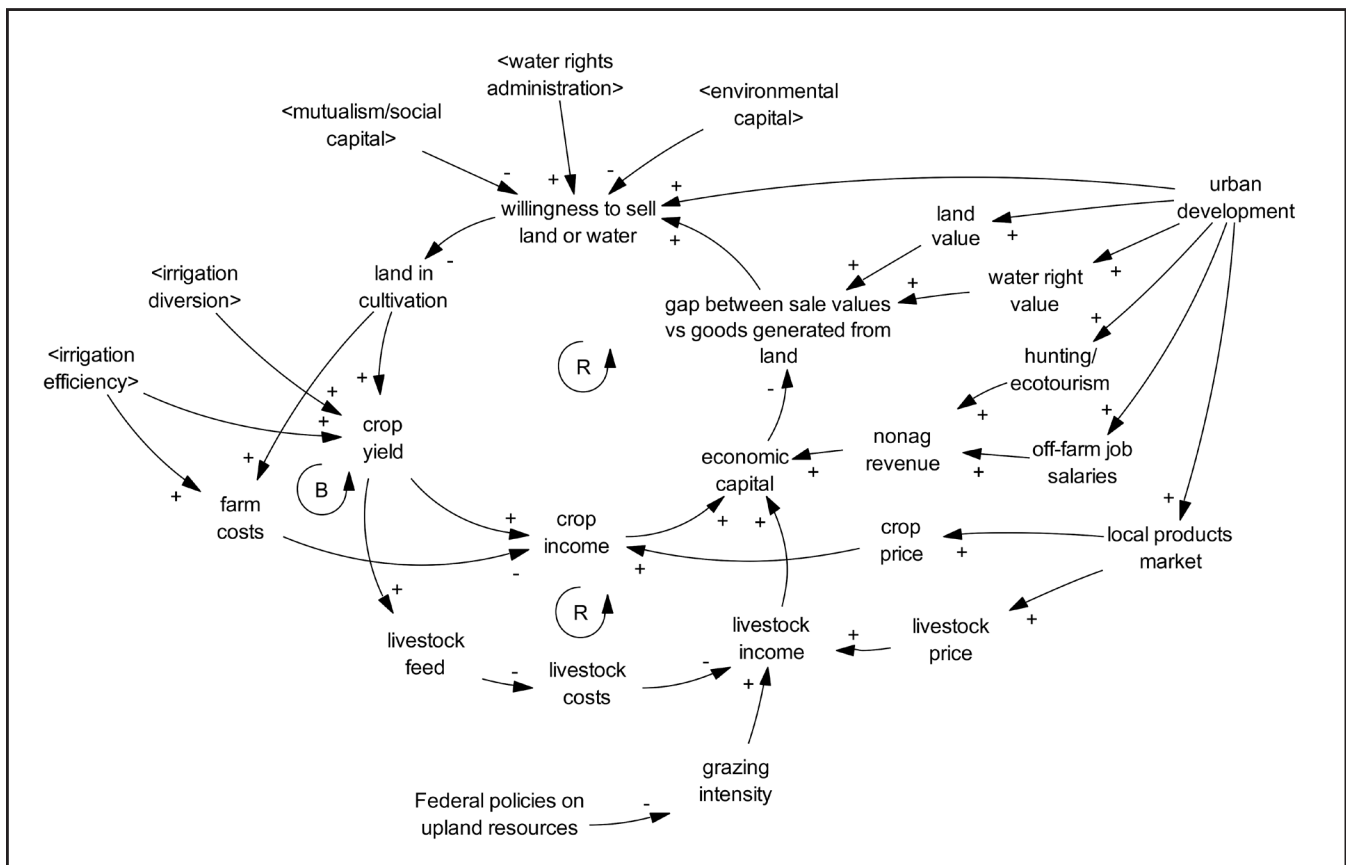
**Figure 2. Hydrology causal loop diagram.** The hydrology causal loop diagram shows important feedback loop processes between streamflow, irrigation diversion, groundwater recharge and storage, and water rights administration (described in the *Hydrology* section). Variables contained within the arrowheads (e.g., <acequia governance>) indicate linkages with the other model components: ecosystem, land use and economics, and mutualism and community dynamics.

ridors, stream bank stabilization), which links the hydrology component with the ecosystem component as described below. (See “Surface Water and Groundwater Interactions in Acequia Systems of Northern New Mexico” chapter for more information.)

## Ecosystem

The ecosystem CLD connects key environmental components, primarily “riparian habitat” (which supports “ecosystem diversity and function”) and “shallow groundwater,” both of which support and direct natural resource management efforts in acequia systems (Figure 3). Shallow groundwater storage is the primary source of water for “riparian habitat” (noted as “available water for ecosystem use”), which reduces groundwater available through “riparian water uptake.” “Shallow groundwater” is also influenced by “groundwater recharge” (which improves water levels), “domestic pumping” (which reduces water levels), and agricultural land use and practices (i.e., “irrigation diversion,” “irrigation efficiency,” and “soil moisture” levels, each of which influences “water seepage” into “shallow groundwater” stocks). In turn, these factors drive the “available water for ecosystem use,” including “riparian habitat,” which provides “ecosystem diversity and function” unique to acequia systems.





**Figure 4. Land use and economics causal loop diagram.** The land use and economics causal loop diagram displays several feedback loops that influence irrigators' land use decisions, including major economic drivers, such as urban development and the linkages with hydrology, ecosystem, and mutualism and community dynamics components. Variables contained within the arrowheads (e.g., <water rights administration>) indicate linkages with these other model components.

that provides feed resources for livestock when they are not grazing in the uplands during the primary grazing season. However, grazing management decisions in the uplands are tightly restricted by federal land agencies, and as such, public policy (shown as "Federal policies on upland resources") is a major driver of livestock "grazing intensity." "Grazing intensity" feeds back to influence vegetation diversity, density, and cover (major determinants of upland soil moisture and groundwater recharge; Figure 2). For generations, parcientes used the area as a **commons** to graze livestock and to hunt and fish. Now those areas are protected and managed as federal land (i.e., U.S. Forest Service or U.S. Bureau of Land Management). Stocking rate decisions are complex and may be driven by a combination of livestock economics, forage productivity in the uplands and acequia valleys, the amount of time that parcientes spend in agriculture, and federal land policies. In general, livestock income has shifted over time depending on parcientes' ability to grow hay or find winter feed resources. However, the "grazing intensity" that parcientes

have been allowed has been reduced over time due to federal policies on upland resources (Lopez et al., 2017).

"Crop income" and "livestock income" are both important to local "economic capital." Economic capital grows with the income returns from agriculture generated through crop and livestock production. Non-agricultural revenues, such as those from "hunting/ecotourism" and from "off-farm job salaries" of acequia members, also contribute to "economic capital." As both resource allocations (e.g., through "water rights administration") and the "willingness to sell land or water" change, "land in cultivation" is either reinforced (as land and water remain in local acequia use and for agricultural production) or diminished (as land and water are sold for development or other non-agricultural uses).

As land in cultivation diminishes or becomes more fragmented, so does the number of farms held by traditional families. The sustainability of many community traditions is at risk when fewer irrigators or community members participate due to divestment of their land and





Lastly, “community investment” is also tied to water management and water governance (i.e., election of **commissioners** and **mayordomo**, or ditch manager, who manage water at the local level), both of which are key factors in their ability to adapt to seasonal and longer-term climate changes such as drought. Effective managers combine hydrologic and sociocultural strategies specific to their individual acequia to respond to changing stream conditions (e.g., *repartimiento*, or customary division of water along the ditch; *auxilio*, or multiple ditches that share diversions during droughts or other emergencies; and *sobrantes*, or the surplus or leftover water to be used by an agreed upon ditch or second party). Similarly, leaders oversee ditch maintenance and improvement and help resolve disputes between irrigators. These leadership features enhance the “mutualism and social capital” accrued within the acequia community by encouraging and facilitating participation by parcientes in acequia traditions. (See “The Roots of Community in the Northern Rio Grande: Acequia Mutualism, Cultural Endurance, and Resilience” chapter for more information.)

### Integrated causal loop diagram of a sustainable and resilient acequia system

Along with the individual CLDs that describe the detailed dynamics of each major acequia component, we constructed a high-level CLD that crosscuts component boundaries between hydrology, ecosystem, land use and economics, and mutualism and community dynamics. The integrated CLD displays important feedback loops between economic, natural, and social capital to the internal workings of the acequia (Figure 6). From each component, acequias generate:

- “natural capital,” arising from hydrology and ecosystem dynamics.
- “acequia mutualism and social capital,” arising from community dynamics, such as “involvement in the community” (and stewardship of traditional acequia practices), local knowledge transmission (noted as “local knowledge transmitted”), and “cooperation over resource allocations” through effective water rights administration.

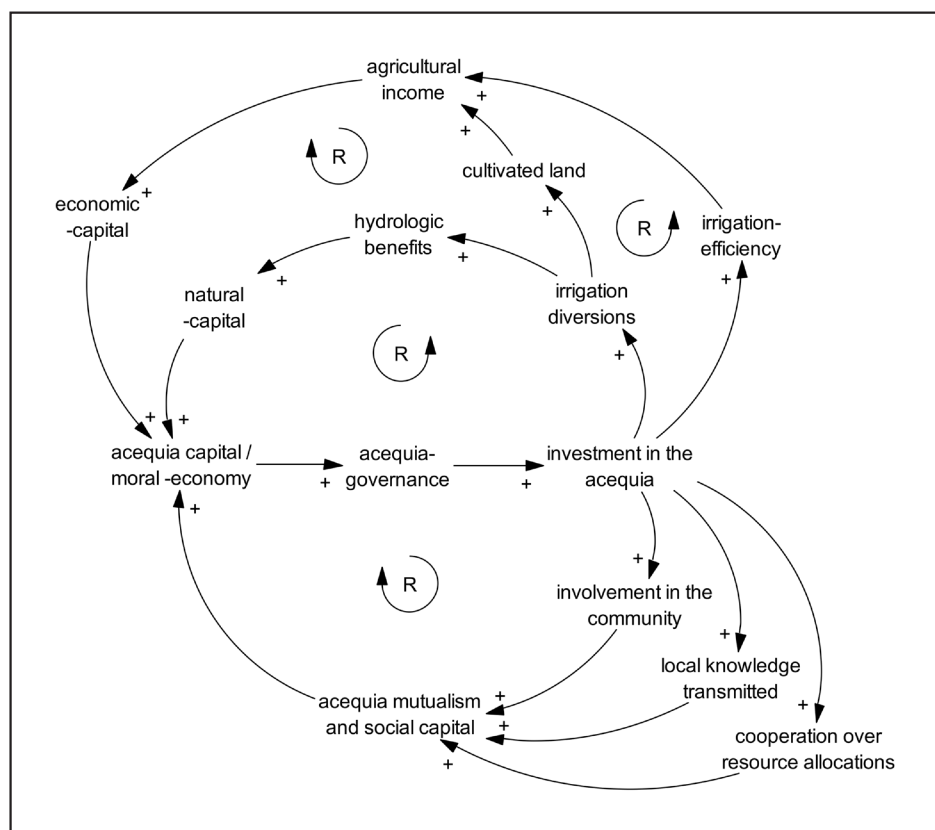


Figure 6. Integrated causal loop diagram of a sustainable and resilient acequia system.

- “economic capital,” arising from land use and economic dynamics, beginning with irrigation and the “agricultural income” it creates and supports.

Together, these capital stocks collectively contribute to form the overall “**acequia capital/moral economy**” (Figure 6). Acequia capital, or the local moral economy, may be defined as a stable economy based on goodness, fairness, and justice. In this economy, participants cooperate and avoid economic free-rider problems, where one party unfairly benefits at the cost of another, and manage environmental externalities like soil erosion, flooding, or wildfires (Baumol, 1952; Buchanan and Stubblebine, 1962). Here, “acequia governance” is the common, critical variable linking all of the important capital stocks to local activities of the acequia, which reinforces “investment in the acequia” (e.g., community participation, infrastructure maintenance, etc.) and therefore the hydrologic, economic, and community benefits that drive each capital stock. When working properly, acequia activities and the associated capital stocks reinforce and support one another (known as **virtuous cycles**). However, when there is a breakdown in acequia governance, it reinforces a potential continuous breakdown in acequia activities and capital accumulation (known as a **vicious cycle**) unless adaptive action is taken to improve local governance. For acequias

to remain sustainable and regenerative, “acequia governance” (including improved participation and leadership development) is a key leverage point likely to have wide ranging benefits to acequia systems.

### **FROM CLDs TO QUANTITATIVE MODELING: PUTTING NUMBERS AND EQUATIONS TO THE ACEQUIA CLDs**

Using the above CLDs, we developed a quantitative SD model to integrate the key relationships and feedback loops driving each acequia function, specifically the relationship between community structure and resource management. The model centered on the major **stocks-and-flows** of the acequia. Stocks-and-flows represent areas of material accumulation and methods of transfer or movement. Primarily these are used for physical goods or quantities, e.g., crops, livestock, or people, but they can also be applied to sources of information or qualitative features such as acequia mutualism. Stock-and-flow linkages in the acequia include feedbacks between hydrology, ecology, community, and economics described above. Rather than provide a detailed account of the mathematical development of the model here, we will briefly describe the model and summarize key high-level results from the initial testing process (readers with interest in the model details are encouraged to see Turner et al. [2016b], an open-access article that can be downloaded or provided free of charge, for a description of the model, the model equations, and the process of formal model testing). The model was formulated in PowersimStudio using stock-and-flow equations to represent the key acequia processes described in the preceding sections: *Hydrology*, *Ecosystem*, *Land use and economic dynamics*, and *Mutualism and community dynamics*. The model was calibrated to real world data (1969–2008) for agricultural profits, community size, land use (agricultural versus residential), cattle herd sizes, and Rio Grande streamflows associated with the Alcalde, NM, community. Model evaluation criteria indicated that the model reproduced dynamic behaviors exhibited by the observed acequia system. Using **sensitivity analyses** (a form of model testing by changing the original model assumptions), Turner et al. (2016b) identified agricultural profitability (crop and livestock), community demographics (percentage of population having local historical roots), and land use (irrigated or residential/built-up) as key determinants of acequia system responses to changing conditions. Results also pointed to community mutualism as a leverage point for sustaining linkages between natural and human systems that increase acequia resilience. Below, we outline several additional tests applied to the acequia model based on alternative historical possibilities (i.e., trajectories in economic and environmental conditions that did not come to fruition, but could have [Srinivasan, 2015]) to examine the acequia system response to these various unforeseen conditions, and then we sum-

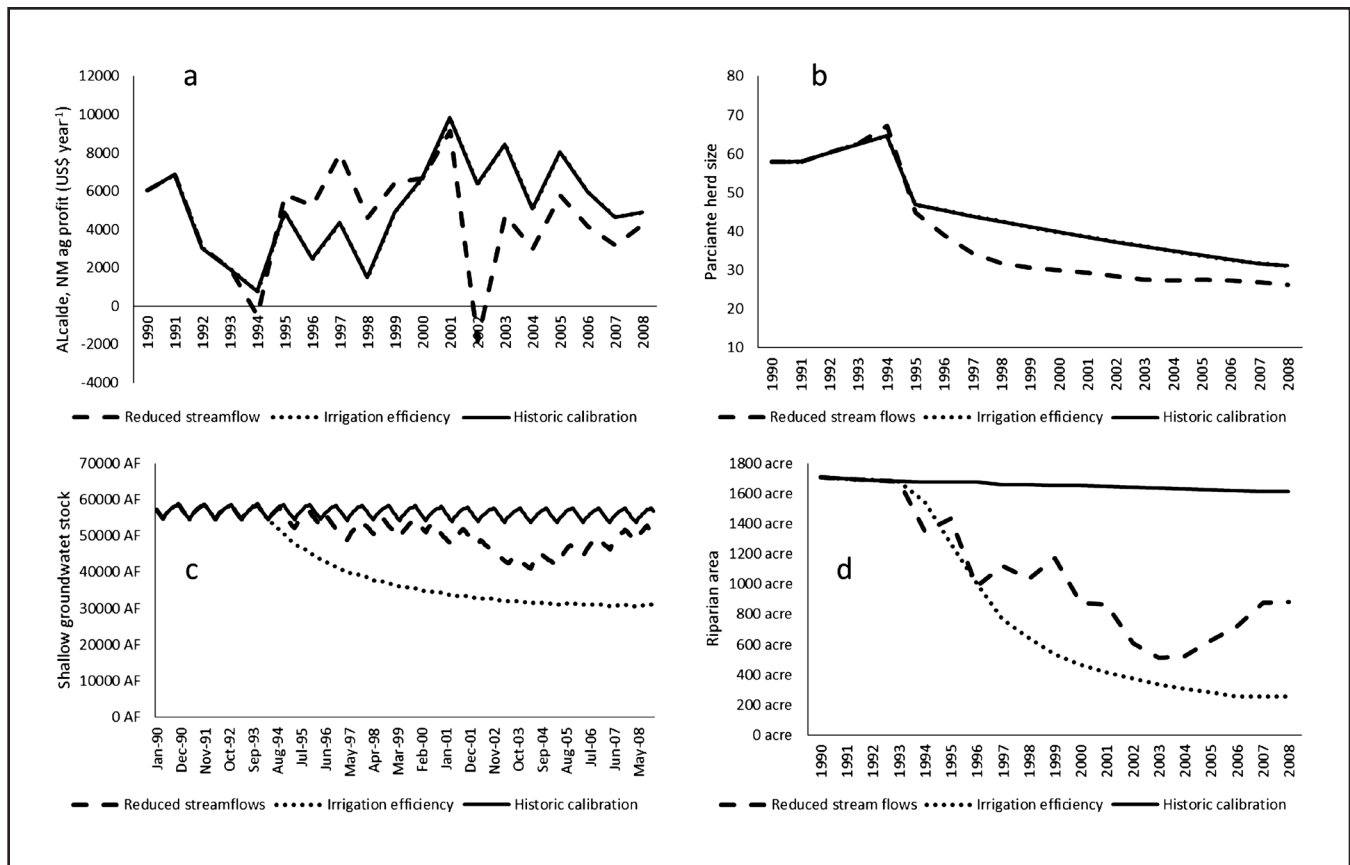
marize the potential implications for future acequia management and research.

### **SCENARIO TESTING METHODS TO EXPLORE ACEQUIA RESILIENCY**

Using the fully parameterized quantitative acequia model (Turner et al., 2016b; available at <http://www.mdpi.com/2071-1050/8/10/1019>), we tested seven scenarios relevant to three general components of acequia community function: hydrology, agricultural productivity (cropping and grazing), and acequia mutualism and sociocultural values. An overview of each test is described in Table 1. Tests represented changes in policy, strategy, or economic conditions aimed at improving acequia function or a pressure that could threaten the viability of the acequia as it currently functions. By performing tests of the model such as these, we hoped to gain a better understanding of the resiliency of acequia systems by measuring the magnitude of change created by altering different parameter values within the model. Model parameter changes that lead to small or modest changes in acequia function point toward resiliency of the system regarding that specific acequia component, while large changes observed in acequia function likely point to aspects susceptible to risk or breakdown. Since little is certain regarding expected changes in economics, climate change, or cultural shifts in the mid- to far-future, we ran the scenario tests on the calibrated model for years 1993–2008, which allowed for visual comparison of acequia performance from a given scenario with the historical trajectory of what actually occurred. Results are shown and described below, including time-series plots illustrating noteworthy changes to the acequia. The time-series plots resulting from each scenario are shown only for years after the test was initiated (i.e., after 1993) rather than over the entire calibration period (40 years) to better illustrate the results.

#### **Hydrology tests**

The two hydrology tests considered a prolonged threat (i.e., drought that reduces snowpack and precipitation, which are the main sources of streamflow) and commonly proposed water conservation strategies used in many regions globally (i.e., ditch or canal lining and drip irrigation applications) (Figure 7). In the first test, a 75% reduction in streamflows was applied in 1993 and remained until the end of the simulation in 2008. Prolonged reductions in streamflows due to long-term drought had a negative impact on agricultural profit (-13% mean difference) due to a combination of lower crop production in years when streamflow could not support irrigation ditch flow (Figure 7a), as well as the reduced herd sizes resulting from lower forage reserves (Figure 7b)—although herd liquidation created short-term economic gains from culling livestock. Agricultural activities such as crop production were able to respond and recover in subsequent years, but livestock became the lim-



**Figure 7. Hydrology model test results.** Results from the hydrology tests applied to the model, illustrating a) agricultural profitability (\$ per year), b) parciate cattle herd size (in livestock head), c) shallow groundwater stock (acre-feet), and d) riparian (non-bosque) area (acres). (Note: some projections may be overlapping.)

iting factor for full recovery in agricultural profits in the longer-term. On the other hand, reduced flows had more lasting effects on shallow groundwater stocks (Figure 7c; -11% mean difference) and the riparian (non-bosque) area (Figure 7d; -42% mean difference), creating a shift in their function (technically, this is called a behavioral shift since the new behavior over time is dramatically different than the original behavior). These longer-term indicators needed up to 10 years to return to near their condition prior to the perturbation (in the case of groundwater stocks) or failed to recover fully (in the case of the riparian [non-bosque] area; Figures 7c and 7d).

One common strategy to cope with water shortages in semiarid regions relying on surface water supplies for irrigation is to line ditches to reduce seepage losses and invest in drip technology to regulate water delivery directly to the plant root zone, minimizing field seepage and runoff. When these strategies were applied to the acequia model, agricultural profit was mostly unchanged, but other important acequia functions were dramatically hindered. Shallow groundwater stocks were reduced nearly 50% of their levels before lining and drip irrigation installations (due to signifi-

cant reduction in shallow groundwater recharge as a result of irrigation system upgrades; Figure 7c). Riparian area supported by ditch and crop field seepage was nearly eliminated after 10 years (from 1,600 to 200 acres [ac], or -61% mean difference over the tested time period; Figure 7d).

### Cropping and grazing tests

The three tests relating to agricultural economics included scenarios for increased vegetable prices (i.e., lettuce and spinach; +100% from a conservative \$2/lb baseline, based on Hecher et al. [2014]), reduced stocking rate policies for livestock (from 20 ac per animal unit to 40 ac per animal unit, or a reduction in stocking rate  $\approx$ 50%), and increased alfalfa and hay prices (+50% from historical values; a dual-response test since irrigators can either export hay or use it to feed their own livestock; Table 1). Each of these tests created significant behavioral shifts in acequia community functions (similar to the hydrology tests, model changes were made in 1993 and held until 2008).

Improved crop prices had no noticeable effect on herd sizes and only marginal impacts on acequia valley land in cultivated agriculture (Figure 8a and 8b). However, signifi-



**Table 1. Overview of Tested Scenarios.** An overview of each scenario test specifying model component, type of scenario, the nature of the test (improvement or threat), the variables in the model used to implement the test, and the percentage change from the observed (calibrated) quantities used relative to the calibrated model.

Model component	Type of scenario	Nature of test	Parameters used	Calibration (1969–2008)	% change from calibration (1993–2008)
<b>Hydrology</b>	Improvement	Enhance irrigation efficiency (ditch lining and drip irrigation)	Ditch and crop field seepage rates	7–15% of ditch flow; 16% of applied irrigation <sup>1</sup>	-100% from observed seepage rates
	Threat	Streamflow reduction due to long-term drought	Stream inflow	Observed Rio Grande monthly streamflows <sup>2</sup>	-75% from observed flows
<b>Cropping and grazing</b>	Improvement	Rising prices due to specialty crop market development	Vegetable prices	\$0.10–2.00 per lb <sup>3</sup>	+100% in vegetable prices
	Threat	Reduced grazing permits due to federal policies	Acres required per animal unit	20 acres per animal unit <sup>4</sup>	-50% stocking rate adjustment (or 40 acres per animal unit)
	Improvement and/or threat	Improved alfalfa prices for growers but higher hay prices for livestock	Forage price per ton	\$32–196 per ton <sup>5</sup>	+50% in forage prices
<b>Sociocultural</b>	Improvement	Rising number of family members returning to acequia	Generational transfer rate goal	90% of possible absentees return <sup>4</sup>	+10% in absentees returning
	Threat	Escalating off-farm wages due to urban growth	Off-farm wage rate	\$2.50–16.00 per hour <sup>6</sup>	+50% in urban wage rates (opportunity costs)

<sup>1</sup> See Fernald and Guldán (2006), Ochoa et al. (2007), Ochoa et al. (2009), and Fernald et al. (2010).

<sup>2</sup> From usgs.gov.

<sup>3</sup> Lettuce and spinach prices extrapolated from Hecher et al. (2014); \$/lb value based on \$2/lb in 2008 and discounted to the beginning of simulation at 8%.

<sup>4</sup> Calibration determined values.

<sup>5</sup> From U.S. Department of Agriculture, National Agricultural Statistics Service.

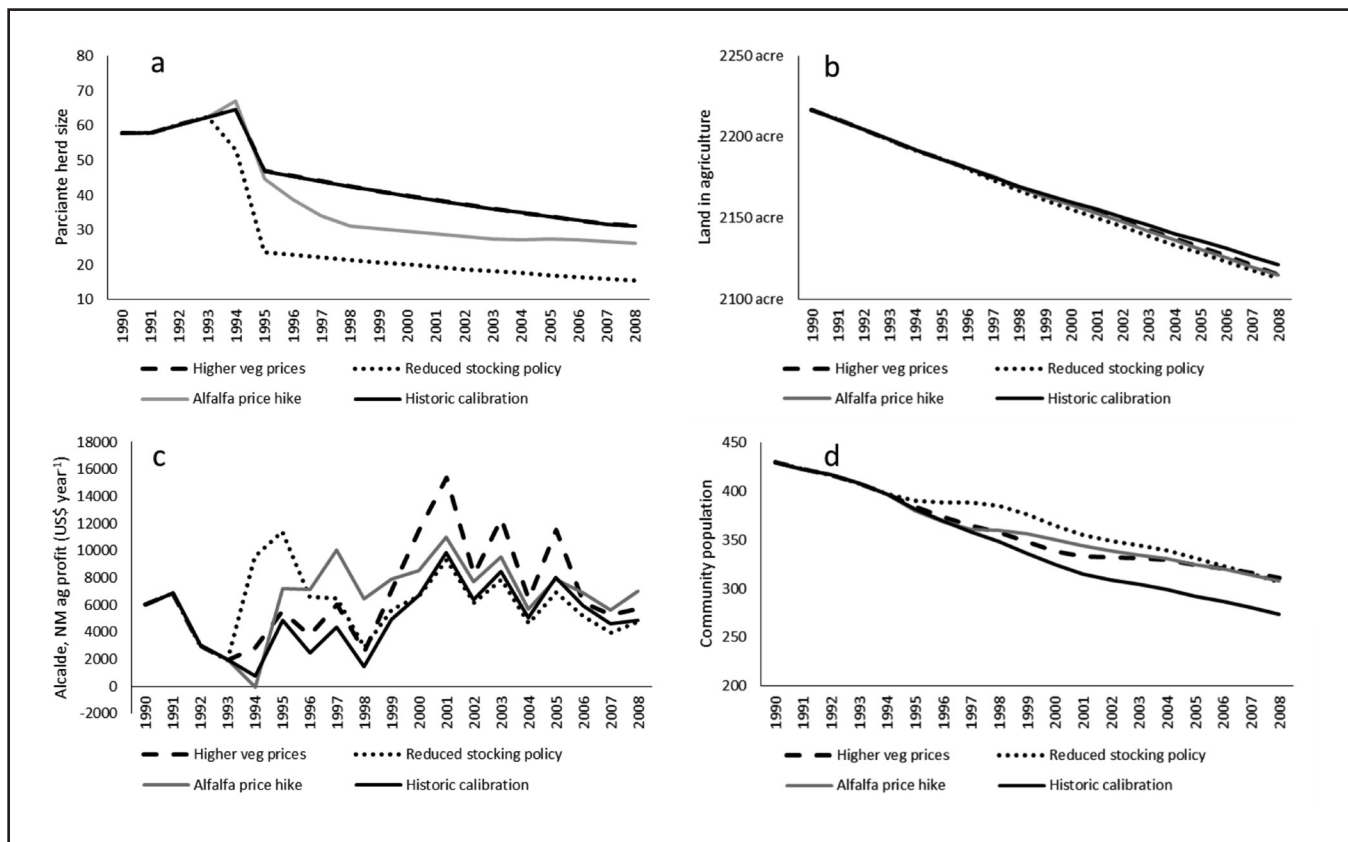
<sup>6</sup> From U.S. Bureau of Economic Analysis.

cant improvements in agricultural profitability (Figure 8c) helped keep more people tied to the acequia community (+5% of baseline average; Figure 8d).

A change in federal land policy restricting herd sizes created several short- and long-term consequences. First, the restriction of grazing animal permits on public land intuitively forced managers to cull over 50% of their respective herds (from near 60 to 20 head; Figure 8a). The act of herd liquidation created much larger livestock revenues than normal, which enhanced profitability in the short-term but reduced long-term profit due to smaller herd size potentials (Figure 8c). The profit created through herd liquidation bolstered irrigators' financial savings, which slowed community population decline (in the short-term) until agricultural profits reached their new, lower expected

values, upon which the decline continued in the longer-term (Figure 8d).

Lastly, the acequia alfalfa and hay enterprise represents an important characteristic that links the irrigated valley to the upland resource by providing valuable forage resources for winter livestock feeding. The forage price test therefore represented a possible dual effect hypothesis (both a potential improvement and a threat) since increased value of forage and hay could either be an acequia threat (through increased livestock feeding costs) or an acequia opportunity (through increased export of forage to increase cropping profitability). Increased forage values and therefore feeding costs necessitated reducing livestock herds by approximately 50% (Figure 8a). Similar to the reduced stocking rate policy, herd liquidation



**Figure 8.** Cropping and grazing model tests. Results from the cropping and grazing tests, illustrating changes in a) pariente herd size (in livestock head), b) land in agricultural production (acres), c) agricultural profits (\$ per year), and d) community population (persons). (Note: some projections may be overlapping.)

enhanced agricultural profitability in the short-term; however, the higher alfalfa values aided in maintaining higher than expected profit in the longer-term as more alfalfa production was sold rather than fed to livestock (Figure 8c), which was also a benefit to the rural community stability (Figure 8d).

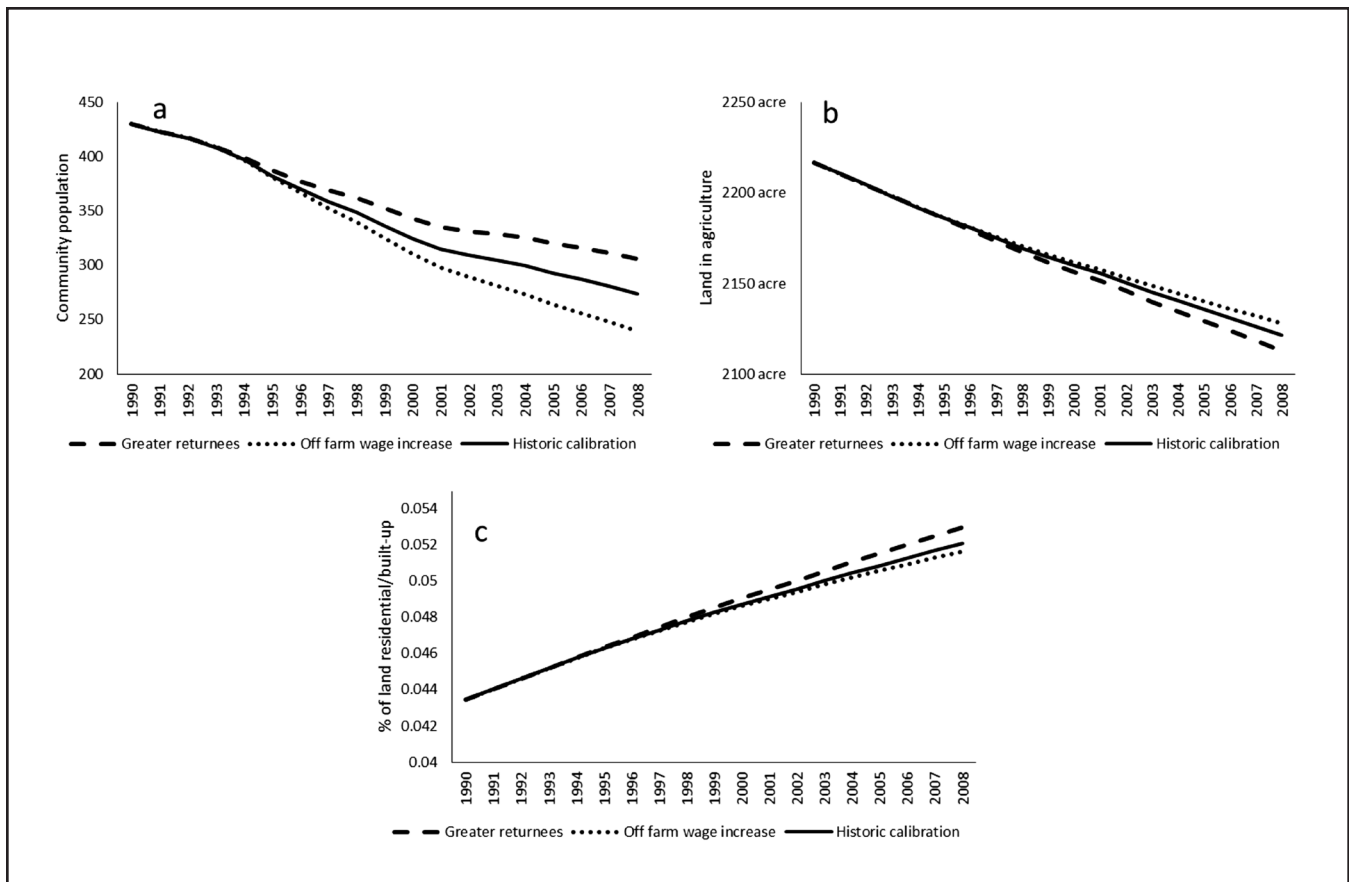
### Mutualism and sociocultural tests

We considered two mutualism/sociocultural tests: raising the number of family members returning to the acequia and increased off-farm wages due to urban growth. Unlike the hydrology and cropping and grazing tests, which produced some behavioral shifts in acequia function, the sociocultural tests created numerical sensitivity (i.e., the shape of the trend-lines are the same, but the slope was either steeper or shallower; Figure 9). The increased arrival rate of returning family members to the acequia slowed the decline in population and slightly reduced land in agriculture to accommodate the new residents. More interestingly, increased off-farm wages pulled some members out of the community (i.e., the opportunity costs of remaining in the acequia were much greater), therefore reducing the population (Figure 9a). With fewer community members remaining, internal

population growth slowed and reduced residential land demand (Figure 9c), allowing land that was left by absenteers or that could have been developed to remain in agricultural production (Figure 9b). No significant changes were observed in hydrology, cropping or herd patterns, or agricultural profitability as a result of either increasing returnees to the acequia or increased off-farm wages for off-farm work.

### DISCUSSION AND IMPLICATIONS

In this chapter, we've explored the multifaceted and diverse connectivity of interacting feedback processes within an acequia community, including hydrologic, ecological, agricultural, economic, and sociocultural feedbacks. Some of the important feedbacks include the balancing processes between streamflow and irrigation (i.e., irrigation diversions may reduce streamflow unless streamflow is limiting and diversions cease) or the reinforcing processes between land use and financial returns (i.e., cultivation and agricultural economics self-reinforce one another in either a virtuous or vicious cycle). Each of these processes is influenced by critical functions, such as water rights administration, and are likewise embedded in the sociocultural processes that build and sustain acequia



**Figure 9. Mutualism and sociocultural model tests. Results from the sociocultural tests, illustrating changes in a) community population (persons), b) land in agricultural production (acres), and c) percentage of land in residential or built-up condition (% of total land). (Note: some projections may be overlapping.)**

mutualism and the local moral economy. Because of this extraordinary complexity, many acequia feedback connections aren't easily recognized or managed.

Therefore, to better understand the potential implications that future economic, policy, or environmental changes will have on acequia communities and infer the long-term consequences that various forces will have on acequia systems, we utilized an acequia system dynamics model to test multiple conditions that are likely to threaten acequia function (e.g., prolonged drought, increased off-farm wages, reduced allowable stocking rates on public land) or strategies or scenarios that are often aimed at improving acequia function (e.g., employment of water conservation strategies, such as ditch lining or drip irrigation; improved commodity prices; increasing the number of returnees to the acequia). Although the sample size is small, several key points may be made based on previous modeling work (Turner et al., 2016b) and the analyses presented here:

- **Hydrology:** Many variables were fairly resilient to prolonged drought (e.g., sociocultural and community variables; agriculture, depending on the relative streamflow volume; and groundwater storage). These results are largely due to the fact that the model was tested for a community mimicking Alcalde, NM, where the Rio Grande flow is relatively high (with respect to acequia water use). Results are expected to be different for acequias on small river systems where irrigation demand is of similar magnitude to that of the available streamflow. However, common water conservation strategies employed to cope with water scarcity—ditch lining and drip irrigation—turned out to be fixes that backfire on the hydrologic functioning of the system, even with the high flow rates associated with the Rio Grande source. By restricting water seepage, the groundwater aquifer stock, a key reservoir for domestic and other uses when the ditch is dry (such as irrigation for winter gardening), was diminished and thereby put the acequia community in a less resilient position when not in the irrigation season.

- *Cropping and grazing:* Increased vegetable prices, which may be achieved through new marketing channels designed for locally sourced foods, had a positive impact on profitability, thereby facilitating increased numbers of residents to remain in the acequia, without jeopardizing land use or livestock production. Conversely, changes in federal land policy that determine *parciantes'* cattle herd stocking rates created agricultural constraints that were more likely to have broader, sweeping impacts to acequias since the proposed changes alter the production system capacity for irrigator-ranchers (fewer livestock→ lower profitability→ continued community population decline). Other, more dynamic factors, such as changing forage values, may produce trade-offs in acequia functions (fewer livestock→ greater forage marketing potential→ increased hay sales and profit) as irrigators seek to maximize returns in single enterprises rather than stability in their diverse enterprises.
- *Sociocultural:* Although the sociocultural tests did not show any behavioral shifts in acequia components in the short-term, they did create significant changes over time. Given the resiliency or inertia of the system to other simple parameter changes (e.g., reduced streamflow or increased crop prices), the impact of greater returns to the acequia or increased off-farm wages was quite significant. This is due to the central and important role that the sociocultural processes have to acequia function, illustrated in Figure 6, and reinforces the importance of effective acequia leadership, engagement, and governance to sustain acequia functions.

## CONCLUSIONS

In this chapter, we provided an overview of the important feedback processes that crosscut the various components of an acequia system, including hydrology, ecology, land use and economic dynamics, and mutualism and community dynamics. We developed several causal loop diagrams illustrating the core feedback processes and relationships. These relationships were then tied together in a quantitative system dynamics model (Turner et al., 2016b). Through previous modeling work, we identified several key factors determining acequia system resilience, including agricultural profitability (crop and livestock), land use (irrigated land relative to residential/built-up), and community demographics (percentage of population with historical roots). Here, we tested the model for a variety of alternative scenarios (some threats, some improvements) to measure the changes within the acequia system in order to better understand responses to uncertain future conditions and management. Results showed that commonly suggested water conservation strategies could turn into a “fix that backfires” since myriad other hydrologic functions were reduced, that changes in federal

land policies (favorable or unfavorable) are likely to have disproportionate effects on the acequia compared to other forces, that changing forage economics could have both positive and negative outcomes for acequia agriculture and communities, and that acequia systems are quite resilient to internal sociocultural changes. The key feedback loops in Figure 6 also demonstrated these relationships between acequia governance and economic capital (e.g., agricultural profit), natural capital (e.g., hydrologic and ecosystem function based on irrigation, which is driven by land use), and acequia mutualism/social capital (which is strongly influenced by those in the community understanding and practicing the historic traditions). Besides the quantitative modeling results, employing the SD method to investigate acequia function has aided in the recognition of and respect for the complexity of acequia communities and the irrigation systems they manage. Admiring this complexity when challenges arise will be a critical first and ongoing step in adaptive planning and local policy and strategy development since any action taken will inevitably influence other components and livelihoods throughout the system.

## ACKNOWLEDGMENTS

This research was funded with a grant from the National Science Foundation Coupled Natural and Human Systems Program (# 1010516 to Fernald et al.). The authors wish to thank Drs. Sam Fernald and Steve Guldán as well as Adrienne Rosenberg for their extremely helpful comments and suggestions that improved the chapter. General support was also provided by the New Mexico State University Agricultural Experiment Station and the Dick and Mary Lewis Kleberg College of Agriculture and Natural Resources at Texas A&M University-Kingsville (for author Ben L. Turner). Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525 (for author Vince C. Tidwell).

## REFERENCES

- Arumí, J.L., D. Rivera, E. Holzapfel, P. Boochs, M. Billib, and A. Fernald. 2009. Effect of irrigation canal network on surface and groundwater connections in the lower valley of the Cachapoal River, Chile. *Chilean Journal of Agricultural Research*, 69, 12–20.
- Baumol, W. 1952. *Welfare economics and the theory of the state*. Cambridge, MA: Harvard University Press.



- Boykin, K.G., B.C. Thompson, R.A. Deitner, D. Schrupp, D. Bradford, L. O'Brien, C. Drost, S. Propeck-Gray, W. Rieth, K.A. Thomas, W. Kepner, J. Lowry, C. Cross, B. Jones, T. Hamer, C. Mettenbrink, K.J. Oakes, J. Prior-Magee, K. Schulz, J.J. Wynne, C. King, J. Puttere, S. Schrader, and Z. Schwenke. 2005. Predicted animal habitat distributions and species richness. In Prior-Magee et al. (Eds.), *Ecoregional gap analysis of the Southwest United States: The Southwest regional gap analysis project final report*. Moscow, ID: U.S. Geological Survey, Gap Analysis Program.
- Buchanan, J., and W.C. Stubblebine. 1962. Externality. *Economica*, 29, 371–384.
- Fernald, A.G., and S.J. Guldán. 2006. Surface water-groundwater interactions between irrigation ditches, alluvial aquifers, and streams. *Reviews in Fisheries Science* 14, 79–89.
- Fernald, A.G., P.J. Wigington, Jr., and D.H. Landers. 2001. Transient storage and hyporheic flow along the Willamette River, Oregon: Field measurements and model estimates. *Water Resources Research*, 37, 1681–1694.
- Fernald, A.G., S.Y. Cevik, C.G. Ochoa, V.C. Tidwell, J.P. King, and S.J. Guldán. 2010. River hydrograph retransmission functions of irrigated valley surface water-groundwater interactions. *Journal of Irrigation and Drainage Engineering*, 136, 823–835.
- Gunda, T., B.L. Turner, and V.C. Tidwell. 2018. The influential role of sociocultural feedbacks on community-managed irrigation system behaviors during times of water stress. *Water Resources Research*, 54, 2697–2714.
- Hecher, E.A.D.S., C.L. Falk, J. Enfield, S.J. Guldán, and M.E. Uchanski. 2014. The economics of low-cost high tunnels for winter vegetable production in the Southwestern United States. *HortTechnology*, 24, 7–15.
- Jencso, K.G., B.L. McGlynn, M.N. Gooseff, S.M. Wondzell, K.E. Bencala, and L.A. Marshall. 2009. Hydrologic connectivity between landscapes and streams: Transferring reach- and plot-scale understanding to the catchment scale. *Water Resources Research*, 45, 1–16.
- Lopez, S., A. Cibils, U. Smedly, S. Guldán, A. Fernald, C. Ochoa, and K. Boykin. 2017. Linkages between acequia farming and rangeland grazing in traditional agropastoral communities of the southwestern USA. *Sustainability*, 10, 2021.
- Millennium Ecosystem Assessment. 2005. *Ecosystems and human well-being: Our human planet: Summary for decision makers*. Washington, D.C.: Island Press.
- Ocampo, J.C., M. Sivalpan, and C. Oldham. 2006. Hydrological connectivity of upland-riparian zones in agricultural catchments: Implications for runoff generation and nitrate transport. *Journal of Hydrology*, 331, 643–658.
- Ochoa, C.G., A.G. Fernald, S.J. Guldán, and M.K. Shukla. 2007. Deep percolation and its effects on shallow groundwater level rise following flood irrigation. *Transactions of the American Society of Agricultural and Biological Engineers*, 50, 73–81.
- Ochoa, C.G., A.G. Fernald, S.J. Guldán, and M.K. Shukla. 2009. Water movement through a shallow vadose zone: A field irrigation experiment. *Vadose Zone Journal*, 8, 414–425.
- Rodríguez, S. 2006. *Acequia: Water sharing, sanctity, and place*. Santa Fe, NM: School for Advanced Research Press.
- Senge, P. 1990. *The fifth discipline: The art & practice of the learning organization*. New York: Doubleday Business.
- Srinivasan, V. 2015. Use of counterfactual trajectories in socio-hydrological modeling: The case of Chennai, India. *Hydrology and Earth System Sciences*, 19, 785–801.
- Sterman, J.D. 2000. *Business dynamics: Systems thinking and modeling for a complex world*. New York: Irwin/McGraw-Hill.
- Stromberg, J.C., S.J. Lite, and M.D. Dixon. 2010. Effects of stream flow patterns on riparian vegetation of a semi-arid river: Implications for a changing climate. *River Research and Applications*, 26, 712–729.
- Turner, B.L., H.M. Menendez, R. Gates, L.O. Tedeschi, and A.S. Atzori. 2016a. System Dynamics modeling for agricultural and natural resource management issues: Review of some past cases and forecasting future roles. *Resources*, 5, 40.
- Turner, B.L., V. Tidwell, A. Fernald, J. Rivera, S. Rodríguez, S. Guldán, C. Ochoa, B. Hurd, K. Boykin, and A. Cibils. 2016b. Modeling acequia irrigation systems using System Dynamics: Model development, evaluation, and sensitivity analyses to investigate effects of socio-economic and biophysical feedbacks. *Sustainability*, 8, 1019.
- Van Ness, J.R. 1991. *Hispanos in Northern New Mexico: Development of corporate community and multicomunity*. New York: AMS Press, Inc.

# Coupled Natural and Human System Clues to Acequia Resilience

Sam Fernald, Carlos G. Ochoa, and Steve J. Guldan

---

This chapter highlights research that has illuminated *acequia* landscapes of Northern New Mexico and elsewhere. Working closely with local communities, and led by faculty and staff from New Mexico State University (NMSU), the University of New Mexico (UNM), Sandia National Laboratories, and other universities and institutions around the globe, researchers discovered key elements of acequia survivability. The chapter will treat various aspects of acequia hydrologic processes and will bring together water and society for lessons in resilience.

## WISDOM OF THE ANCIENTS

In 2001, a presentation at a New Mexico Acequia Association meeting touted the benefits of acequias and the water they convey: they maintain the agriculture central to New Mexico's small communities, they keep alive the trees lining the ditches, they protect groundwater quality, and they recharge groundwater. Even the ditch **seepage** water isn't wasted as it returns back to the river from whence it came. Centuries of irrigators who had lived and worked in the acequia-irrigated valleys (Figure 1) understood these bountiful benefits.

In the contentious early 2000s, there were multiplying attempts to purloin acequia water and move it out of the irrigated valleys. In 2003, the New Mexico legislature passed a law requiring that acequias agree to any water transfers out of their acequia systems. With dry years starting in 2002 and increasing water demands, it was more important than ever to have data on water, yet the hydrologic processes of acequias were stored primarily in the hearts and minds of *los ancianos*, the elderly. There were no data! The ensuing group of projects highlighted in this chapter set out to provide the data, and in the process, these projects illuminated hydrologic and social functioning of the acequias as well as the key underpinning forces that keep a community together when faced with existential threats.

## RESEARCH GUIDED BY COMMUNITY INPUT

In 2002, researchers from NMSU secured funding from the U.S. Department of Agriculture to conduct acequia research. They began what would become a long and fruitful research endeavor by meeting with community members to



**Figure 1.** In 2002, NMSU College of Agricultural, Consumer and Environmental Sciences Dean Jerry Schickedanz flew to a meeting in Taos; on board was Sam Fernald, who requested a fly-by of the Acequia de Alcalde. The photo from that flight shows the acequia network that spreads water across the valley to hydrate farms, yards, and ecosystems. (Photo by Sam Fernald, NMSU.)



hear their priorities for acequia research. Some of the first community members to participate were the **commissioners** and the **mayordomo** of the Acequia de Alcalde (Figure 2). Early priorities were to quantify the amounts of water that were seeping from ditches, recharging groundwater, and flowing underground back into the river (from which the water was initially diverted) as well as explore water quality associated with acequia hydrology.

In addition to laying the foundations for future research, the community interactions created a two-way conduit of information between the community members and the researchers. The exchange of ideas between stakeholders and researchers is now recognized as **community science**, one of the most effective approaches to science that creates new understanding on problem solving by looking to the community for identification of critical issues (Figure 3). The Acequia de Alcalde members were early contributors of ideas that launched the researchers on a path of effective community science. Many community members in small towns and villages of Northern New Mexico and the broader acequia-interested community joined the Acequia de Alcalde. Guldán et al. (2013) highlighted the inclusion of community members as key participants in community hydrology research. Even beyond research topic prioritization, community members became key participants in the research, providing access to fields, acequias, and even their own domestic wells. In sum, they provided household perspectives that allowed for critical water and society measurements.

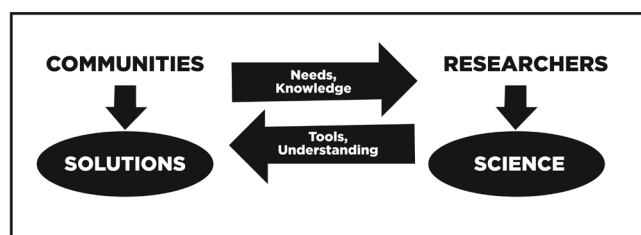
### KNOW WHERE THE FLOW GOES

A key question from the acequia community was, “Where is all the water going?” **Hydrologic budgets** (or water budgets) account for inputs and outputs of water in a defined region, such as a field, farm, valley, basin, or even an entire state. Studies of water budgets (Figure 4) along the Acequia de Alcalde provided an invaluable set of data with key take-home messages about where the water was going. The approach was to use measurement technology to show the fate of acequia water, characterizing the processes and providing the real data.

First, we found that the groundwater in the valley responds to irrigation events and the entire irrigation system (see “Surface Water and Groundwater Interactions in Acequia Systems of Northern New Mexico” chapter). Stream-flow measurements combined with irrigation application testing and groundwater measurements revealed seepage from ditches and fields. Every year during the irrigation season, most of the soils in the valley allow for water to percolate through the root zone and into the shallow aquifer (Figure 5). Each successive irrigation event maintains an elevated water table until irrigation stops in the fall. In the case of the Acequia de Alcalde, ditch flow and seepage from the ditch both continue until late fall. The groundwater in the valley is still somewhat elevated until all ditch



**Figure 2.** Community members and researchers meeting to discuss acequia research needs. The photo, taken in 2002, records a foundational meeting in the NMSU Alcalde Science Center’s shop where researchers listened to the Acequia de Alcalde Commission’s research issues and needs. This meeting helped to chart a path for future research based on local priorities. Shown clockwise from the empty chair are Michael Sanchez, Acequia de Alcalde Commissioner; Bon Diaz, Acequia de Alcalde Mayor-domo; Max Martinez, Acequia de Alcalde Commissioner; David Archuleta, NMSU Alcalde Science Center Farm Supervisor; Steve Guldán, NMSU Alcalde Science Center Superintendent; Sam Fernald, NMSU Professor of Watershed Management; Val Archuleta, NMSU Alcalde Science Center Field Technician; and Alfredo Montoya (not shown), Acequia de Alcalde Commissioner. (Photo by Alfredo Montoya. Used with permission.)



**Figure 3.** Community science for cutting-edge science to provide needed understanding.

flow ceases for the year. At that time, the groundwater starts dropping and continues dropping until the irrigation seepage begins again the following spring.

A summary of the hydrologic budget of the Acequia de Alcalde revealed that, averaged over a three-year period, about 33% of all water diverted from the river percolated below the ditch and fields. On average, crop **evapotranspiration** consumed 7% of the water. The remainder of the

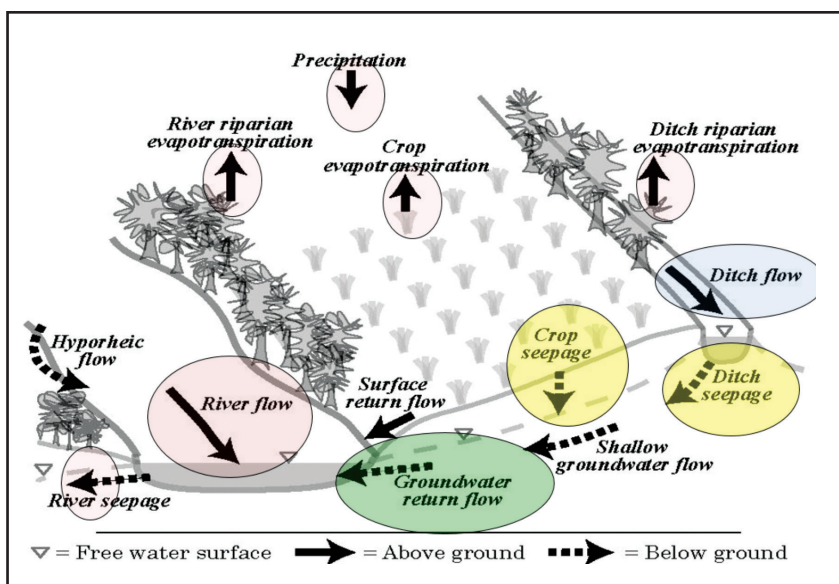
water returned to the river by tailwater via *desagües* or acequia **surface return flows** off of irrigated fields (Fernald et al., 2010). Interestingly, the water that recharged groundwater also found its way back to the river. This return flow was evident in river flow measurements upstream and downstream of the Alcalde valley, a reach of river with no perennial tributaries. During the irrigation season, there was less flow downstream, but after the irrigation season, there was more flow downstream. The irrigation water was being pulled off of the snowmelt peak, distributed to the fields, percolating to groundwater, and slowly returning back to the river from which it came in the fall when streamflows are low (Fernald et al., 2010).

Alcalde represents a relatively wet site, grabbing irrigation water from the Rio Grande mainstem that has **baseflow** (streamflow in between storms or runoff events that is maintained by groundwater contributions) in all but the very driest sections in the driest years. As a proportion of irrigation water applied to agricultural fields, evapotranspiration consumed about 14% of the water along the Acequia de Alcalde. New research—still in progress at the time of this book’s writing—suggests that in drier sites like El Rito, evapotranspiration consumes about 75% of the water.

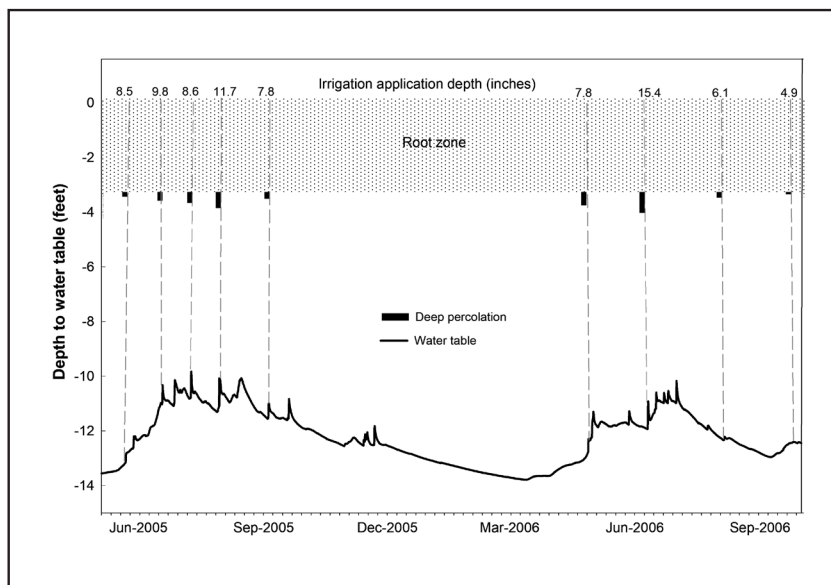
## ECOSYSTEM FUNCTIONS AND LANDSCAPE MANAGEMENT

Complementary studies have shown the value of acequias for many ecosystem functions (see “Acequia Ecosystems” chapter). In these studies, we were able to explore water quality, riparian vegetation, and bird diversity aspects of acequias.

We found that the seepage from ditches and fields adds clean water to the groundwater. Acequia ditch and field seepage diluted groundwater that was slightly higher in dissolved constituents (e.g., nitrate, chloride, sulfate, and others), and water quality improved (Helmus et al., 2009). The seepage supported riparian vegetation, allowing cottonwood tree growth that was supported by acequia system seepage (Cu-



**Figure 4.** Water budget approach to quantify surface water and groundwater flows in an acequia-irrigated valley. Figure depicts surface water (ditch and river) and shallow groundwater.



**Figure 5.** Groundwater increases in direct response to irrigation (based on Ochoa et al., 2011).

sack, 2009) (Figure 6). The riparian areas sustained by acequias in the broader Northern New Mexico region are very important for **biodiversity** (healthy populations of many different species of plants and animals) now and into the future (Samson et al., 2018).

The studies mentioned here only provide a brief smattering of the many functions supported by acequias. Many more remain to be documented, including riparian vegetation for migratory bird flyways, cool water returns to maintain coldwater fishery habitat, and soil moisture retention for riparian plant diversity.





**Figure 6. Riparian vegetation supported by acequia seepage. (Photo by Sam Fernald, NMSU.)**

In addition to ecosystem functions within the irrigated valley, we found that acequia-irrigated farms have an important effect on grazing in the surrounding forest and grassland rangelands (see “The Role of Livestock in Supporting Acequia Communities of Northern New Mexico” chapter). In very dry years, U.S. Forest Service allotment grazing went down, in large part because there was less irrigated forage produced in the valleys due to less irrigation water availability. Conversely, with more irrigation water availability, there was more grazing on forested allotments in the summer because livestock could be sustained with irrigated forage in the winter (Lopez et al., 2018). It turns out that acequia irrigation water support of pastures and forage in the valley impacts livestock grazing covering the adjacent landscape.

### **ECONOMIC SURVIVAL IN ACEQUIA COUNTRY**

As we discovered more and more of the important biophysical functions of acequias, it became apparent that there is critical value for rural communities in maintaining acequia agriculture. Furthermore, there are important external factors that are beneficial for small-scale farming in the valleys of New Mexico and the region supported by acequia irrigation (see “The Role of Livestock in Supporting Acequia Communities of Northern New Mexico” chapter).

Surveys of acequia irrigators in El Rito, Rio Hondo, and Alcalde (Figure 7) indicated that on average acequia agricultural activities provided about 30% of family income, and outside income was used to sustain their farm or acequia-irrigated property (Mayagoitia et al., 2012). If a plurality of acequia irrigators requires external support to maintain their irrigated agriculture, we wondered, *What ties people to the land?*

### **CONNECTIONS TO LAND, COMMUNITY, AND THE MORAL ECONOMY**

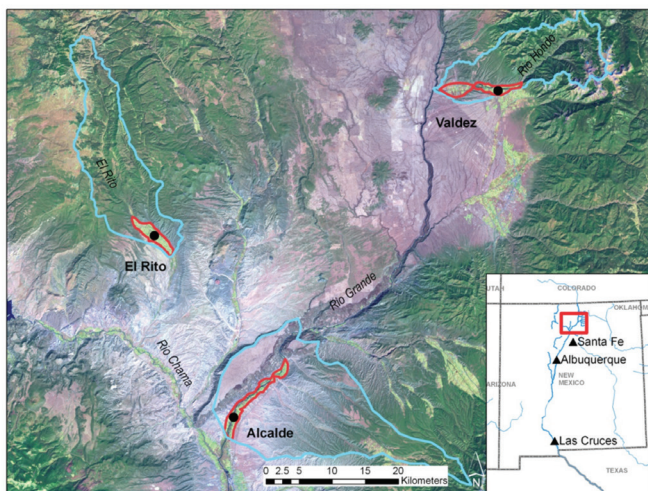
Focus groups and individual interviews revealed an incredibly strong connection to the community and the land. One part of this connection harkened back to the founding irrigators who plunged their shovels into the riverbank to divert water onto the floodplain (Rivera, 1998). The ensuing irrigation system is a physical structure that requires maintenance and cleaning and relies upon local participation. This tangible connection to the land continues to this day in the living history of acequias (Maxwell Museum of Anthropology, 2015). Acequia water management that includes water sharing (Figure 8) is coordinated by the acequia commission, the acequia mayordomo, and participation of the *parciantes* (Rivera, 1998; Fernald et al., 2015; Rodríguez, 2006) (see “The Roots of Community in the Northern Rio Grande: Acequia Mutualism, Cultural Endurance, and Resilience” and “Key Concepts for a Multidisciplinary Approach to Acequias” chapters).

Delving into the psyche of acequia irrigators, our research team wondered what was drawing people to stay when economics did not provide enough support and drought threatened longevity of the water and farming resources. Interviews revealed an astonishingly strong connection to land, place, and their acequias (Fernald et al., 2015; Mayagoitia et al., 2012). Bringing these strongly held values under the umbrella of **moral economy**, we found that the values of tradition, family, and community were as strong or stronger than dollars in pocketbooks. Together, the farming economy and moral economy link people and water to land and community. This connectivity drives sustainability (Fernald et al., 2015; Turner et al., 2016).

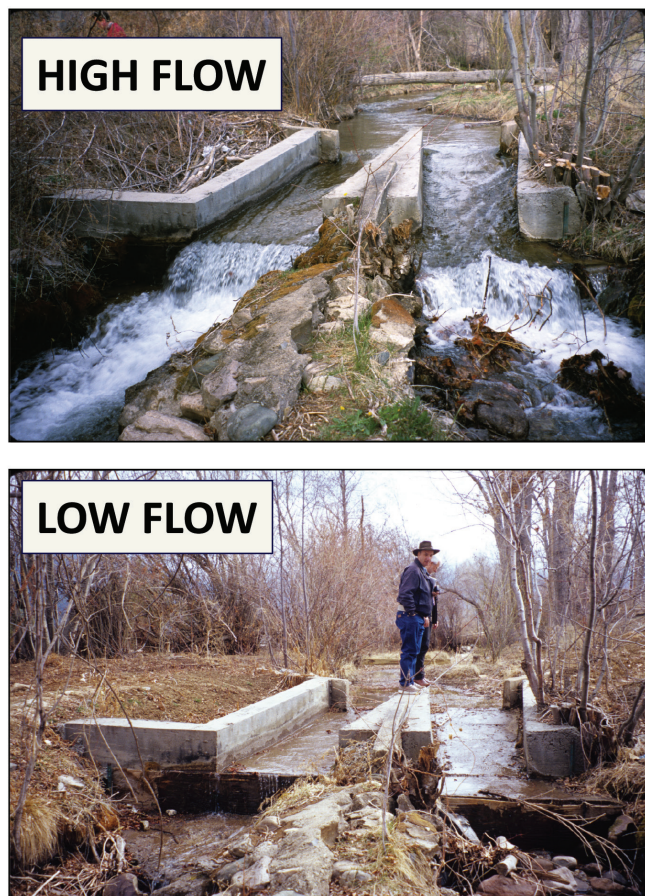
### **SYSTEMS THINKING TO HELP UNDERSTAND CULTURE AND HYDROLOGY**

We used an approach called **system dynamics modeling** to bring together human and natural systems within one analytical framework (see “Connection and Integration: A Systems Approach to Exploring Acequia Community Resilience” chapter). System dynamics is simply a way to solve multiple equations at the same time, and importantly it allows the inclusion of different metrics in the same model (Figure 9). For example, dollars for economy, cubic feet for water, and personal values for moral economy can all be analyzed together for their reinforcing or detracting effect on community resilience.





**Figure 7.** Acequia study communities (black circles), their associated irrigated valleys (red lines), and contributing watersheds (blue lines) (Fernald et al., 2012).



**Figure 8.** Sharing shortage or *repartimiento*, showing even distribution of water to two different acequias during high and low flow. (Photos by Jose Rivera, UNM.)

We found that human-maintained acequia water systems have so heavily impacted hydrology itself that it is impossible to understand hydrology without understanding the supporting human society. We also discovered that for Rio Hondo, sustainability is a feature of acequia communities tied to the combination of hydrologic and community connectivity and resilience.

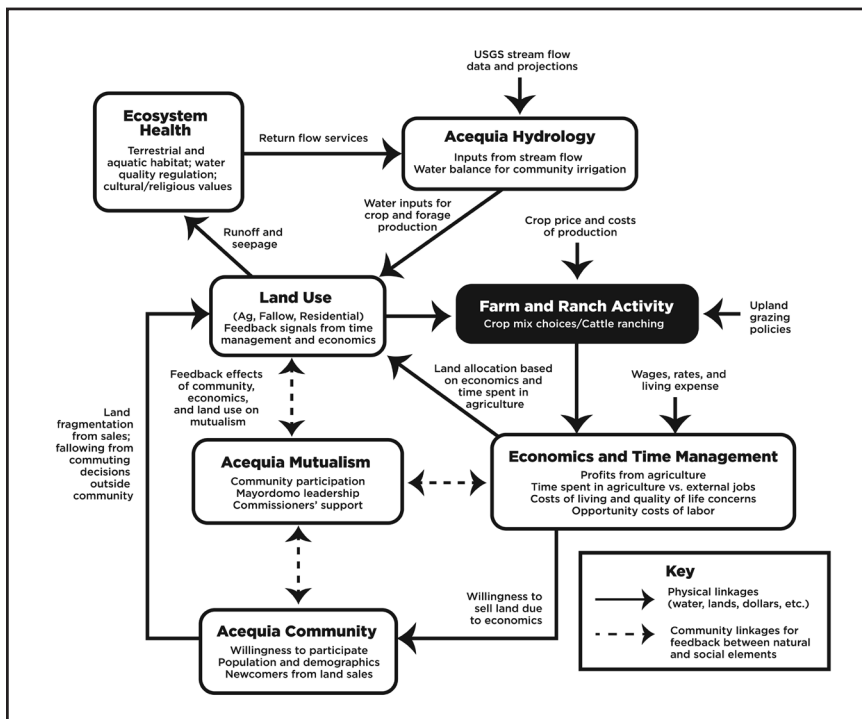
### EXTRACTING CLUES FOR SUSTAINABILITY

Simply stated, the long-term health of acequia communities can be nurtured by maintaining key features: the water delivery system; the largely agricultural land use; the community water management system; the spiritual or intrinsic value of land, water, crops, and animals; and enough outside economic, legal, and political support to bolster the community water delivery and management system. The data provided by this project reinforce the unquantified wisdom passed down through the ages, the wisdom of los ancianos.

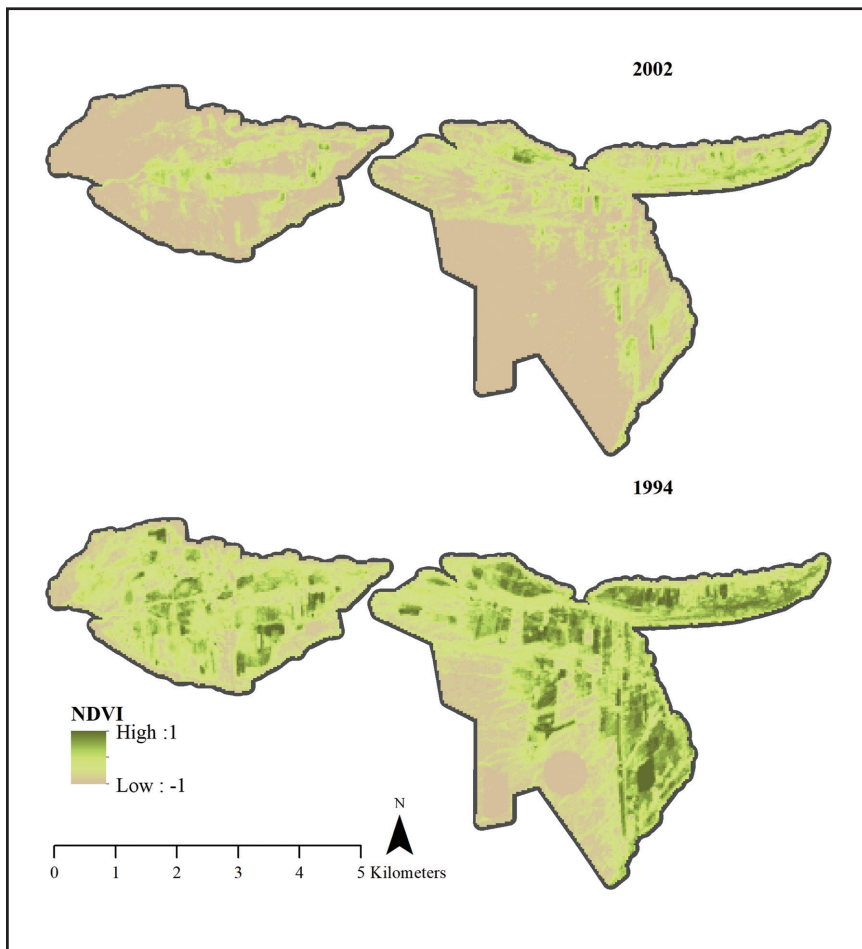
Acequias are a model for resource sustainability because they are adaptable. In wet years, the irrigation intensity increases in valleys across New Mexico. In dry years, the intensity of irrigation decreases. Importantly, there is an integrated community involvement in retaining an irrigated landscape through maintenance of the acequia irrigation network (Fernald et al., 2018) (Figure 10). Human management of each headgate and desagüe allows a personal connection to land and water that results in a resilient system for the region. We found examples in Chile and Spain where acequias function properly and acequia traditions are sustained, even with urban and water demand pressures (Arumí et al., 2009). We are conducting ongoing research to combine analytical equations for resource sustainability with systems science representations of community water connectivity to show long-term natural resource capability.

We are developing a new approach to water-reliant systems that complements Ostrom's ideas of **community resource management** (Ostrom, 1990, 1992). Ostrom's research documented that small, local communities that share resources, such as forests, pastures, and water, over time develop rules to share and care for the resources. In the case of acequias, there is widespread interest in maintaining irrigated landscapes and, accordingly, the network of acequias that provides the irrigation.

Acequia communities have renewable—though variable—water resources, communities that are closely connected in terms of social and ecological systems, and management approaches that are flexible and adaptable. Acequias have survived in New Mexico for many centuries, and the results from our studies indicate that they may remain resilient for many more years to come. The lessons acequias are teaching us are critical for managing water in the arid West and for natural resource management around the world.



*Figure 9.* Conceptual diagram showing each system building block of the acequia model and the linkages between them, similar to other socio-hydrology models (Turner et al., 2016).



*Figure 10.* Landscape irrigated by the Rio Hondo acequias in dry (2002) and wet (1994) years, showing that the irrigated networks are maintained to cover the landscape and that intensity of irrigation (as measured by NDVI—normalized difference vegetation index) varies with available water (Fernald et al., 2018).



## REFERENCES

- Arumí, J.L., D. Rivera, E. Holzapfel, P. Boochs, M. Bil-lib, and A. Fernald. 2009. Effect of the irrigation canal network on surface and groundwater interactions in the lower valley of the Cachapoal river, Chile. *Chilean Journal of Agricultural Research*, 69, 12–20.
- Cusack, C.J. 2009. *Supporting riparian habitat with acequia irrigation systems of the northern Rio Grande region* [master's thesis]. Las Cruces: New Mexico State University.
- Fernald, A., S.J. Guldán, and R. Sabie. 2018. *Traditional hydro-cultural water management systems increase agricultural capacity and community resilience in drought prone New Mexico*, USA. Paper presented at American Geophysical Union Fall Meeting [Abstract H11U-1757], Washington, D.C., December 2018.
- Fernald, A.G., S.Y. Cevik, C.G. Ochoa, V.C. Tidwell, J.P. King, and S.J. Guldán. 2010. River hydrograph retransmission functions of irrigated valley surface water-groundwater interactions. *Journal Irrigation and Drainage Engineering*, 136, 823–835.
- Fernald, A., V. Tidwell, J. Rivera, S. Rodríguez, S. Guldán, C. Steele, C. Ochoa, B. Hurd, M. Ortiz, K. Boykin, and A. Cibils. 2012. Modeling sustainability of water, environment, livelihood, and culture in traditional irrigation communities and their linked watersheds. *Sustainability*, 4, 2998–3022.
- Fernald, A., S. Guldán, K. Boykin, A. Cibils, M. Gonzales, B. Hurd, S. Lopez, C. Ochoa, M. Ortiz, J. Rivera, S. Rodríguez, and C. Steele. 2015. Linked hydrologic and social systems that support resilience of traditional irrigation communities. *Hydrology and Earth System Sciences*, 19, 293–307.
- Guldán, S.J., A.G. Fernald, C.G. Ochoa, and V.C. Tidwell. 2013. Collaborative community hydrology research in Northern New Mexico. *Journal of Contemporary Water Research and Education*, 152, 49–54.
- Helmus, A.M., A.G. Fernald, D.M. VanLeeuwen, L.B. Abbott, A.L. Ulery, and T.T. Baker. 2009. Surface water seepage effects on shallow ground-water quality along the Rio Grande in Northern New Mexico. *Journal of the American Water Resources Association*, 45, 407–418.
- López, S.C., A.F. Cibils, U.R. Smedly, S.J. Guldán, A.G. Fernald, C.G. Ochoa, K.G. Boykin, and L. Cibils. 2018. Linkages between *acequia* farming and rangeland grazing in traditional agropastoral communities of the Southwestern USA. *Sustainability*, 10, 2021.
- Maxwell Museum of Anthropology. 2015. El agua es vida: Acequias in Northern New Mexico. Retrieved June 13, 2019, from <https://maxwellmuseum.unm.edu/exhibits/temporary/el-agua-es-vida-acequias-northern-new-mexico>
- Mayagoitia, L., B. Hurd, J. Rivera, and S. Guldán. 2012. Rural community perspectives on preparedness and adaptation to climate-change and demographic pressure. *Journal of Contemporary Water Research and Education*, 147, 49–62.
- Ochoa, C.G., A.G. Fernald, and S.J. Guldán. 2011. Application of RZWQM for hydrological modeling in Alcalde Basin of Northern New Mexico. In M.K. Shukla (Ed.), *Soil hydrology, land use and agriculture: Measurement and modelling*. Wallingford, UK: CABI.
- Ostrom, E. 1990. *Governing the commons: The evolution of institutions for collective action*. Cambridge, MA: Cambridge University Press.
- Ostrom, E. 1992. *Crafting institutions for self-governing irrigation systems*. San Francisco, CA: Institute for Contemporary Studies.
- Rivera, J. A. 1998. *Acequia culture: Water, land, and community in the Southwest*. Albuquerque: University of New Mexico Press.
- Rodríguez, S. 2006. *Acequia: Water-sharing, sanctity, and place*. Santa Fe, NM: School for Advanced Research Press.
- Samson, E.A., K.G. Boykin, W.G. Kepner, M.C. Andersen, and A. Fernald. 2018. Evaluating biodiversity metric response to forecasted land use change in the northern Rio Grande Basin. *Environments*, 5, 91.
- Turner, B.L., V. Tidwell, A. Fernald, J.A. Rivera, S. Rodríguez, S. Guldán, C. Ochoa, B. Hurd, K. Boykin, and A. Cibils. 2016. Modeling acequia irrigation systems using system dynamics: Model development, evaluation, and sensitivity analyses to investigate effects of socio-economic and biophysical feedbacks. *Sustainability*, 8, 1019.



## APPENDIX

The following excerpt is extracted from the symposium “Acequias and the Future of Resilience in the Global Perspective.” The symposium took place in March 2013 and brought together scholars known for their research on autonomous irrigation systems in various parts of the world with acequia researchers, activists, and community members. Held for two days in Las Cruces, New Mexico, it was free and open to the public. It featured two panels made up of CNHAP team members who reported on their findings, and two panels made up of invited scholars who spoke about their research in Spain, the U.S., Chile, Bali, Peru, Mexico, Morocco, and the Mediterranean. The panels were followed on the second day by an open workshop in which acequia researchers and activists shared ideas and prospects for future research. Below is the symposium program and abstracts; audio recordings of panel sessions and the workshop can be found at the following Cultural Energy link: <http://www.culturalenergy.org/acequia.htm#AcequiasGlobal>

### SESSION 1: CNH PANEL (SATURDAY MORNING)

#### Panel Introductions

“*Multi-Theme Data Acquisition*”—Moderated by Andres Ciblis, New Mexico State University

“*Acequia Hydrology Foundations of Community Resilience to Changing Climate and Land Use*”—Sam Fernald, New Mexico State University (15 min)

“*Ecosystem Services, Faunal Biodiversity and Vegetation Dynamics in Response to Forecasted Land-use and Climate Change within Upper Rio Grande*”—Ken Boykin, New Mexico State University (15 min)

“*The Acequia Model: Local Knowledge and Sociocultural Adaptation in the Northern Rio Grande Watershed Commons*”—José Rivera, University of New Mexico (15 min)

### SESSION 2: CNH PANEL (SATURDAY MORNING)

#### Panel Introductions

“*Data Integration and Modeling the Interplay of Social, Cultural, Economic, and Environmental Factors in an Acequia Community*”—Moderated by Sylvia Rodríguez, University of New Mexico

“*Monitoring and Modeling Hydrologic Connectivity in Semi-Arid Watersheds*”—Carlos Ochoa, New Mexico State University (15 min)

“*Acequia Perspectives on Climate-Change and Population Growth and the Perspectives of Preparedness and Adaptation*”—Brian Hurd, New Mexico State University (15 min)

“*Modeling the Hydrologic/Ecologic/Economic/Social Dynamics of Small Scale Community Irrigation Systems (Acequias)*”—Vince Tidwell, Sandia National Laboratories (15 min)

### SESSION 3: INVITED PANEL (SATURDAY AFTERNOON)

Moderated by Devon G. Peña, University of Washington in Seattle

“*Safeguarding Valencian Acequias: History and Values of a Millennial Water Sharing Culture*”—Luis Pablo Martínez, Directorate General of Cultural Heritage, Valencia, Spain (20 min)

“*Encounters with the Moral Economy of Water: Convergent Evolution and Diffusion in Valencia*”—Paul Trawick, Idaho State University (20 min)

“*Society and Hydrology in a Chilean Andean Watershed: How Poor Knowledge of the Hydrological System Produces Social Conflicts*”—José Luis Arumí Ribera, Universidad de Concepción, Chillán, Chile (20 min)

“*The Effects of Social and Economic Disturbances on the Taos Acequias of Northern New Mexico*”—Michael Cox, Dartmouth College (20 min)

### SESSION 4: INVITED PANEL (SUNDAY MORNING)

Moderated by Steve Guldán, New Mexico State University

“*Regime Shifts in the Morning of the World*”—Steve Lansing, University of Arizona, Santa Fe Institute (20 min)

“*Visible and Invisible Self-Managed Irrigation Organizations*”—Jacinta Palerm, Colegio de Postgraduados, Mexico-Texcoco (20 min)

“*Irrigation Management in Pre-Saharan Morocco: Some Perspectives from the Assag(q)yas of the Ziz Oasis*”—Hsain Ilahiane, University of Kentucky (20 min)

“*Is the Crafting of Self-Governing Irrigation Institutions in the XXth Century Following Elinor Ostrom’s Principles Still Relevant in the Beginning of the XXI Century?*”—Thierry Ruf, Supagro-Institut des régions chaudes, Montpellier, France (20 min)

## ABSTRACTS

### Session 1

#### **Ecosystem Benefits of Traditional Acequia Irrigation Systems in Northern New Mexico in Relation to Climate Change Stressors and Community Resilience (Fernald)**

Investigations into hydrologic impacts of traditional acequia irrigation systems created the foundation for the Acequia CNH project that goes beyond hydrology to also confront sociocultural, economic, and environmental aspects of acequia systems. Our studies began in 2002 in response to local interest in hydrologic benefits of acequias. For the 9 km Alcalde Acequia, we conducted detailed field investigations to determine water budgets and interactions between surface water and groundwater. We found that of the water diverted into acequias, only a small proportion of water was consumptively used by plants. The majority of the water returned to the Rio Grande through surface water and groundwater return flows. The 33% of water that seeped from ditches and fields was temporarily stored for weeks to a few months in shallow groundwater before emerging as river flow. Through this storage and release, the stream snowmelt runoff hydrograph is retransmitted by a period of a few weeks. In the face of climate change with snowmelt projected to occur much earlier in the spring, hydrograph retransmission may ameliorate impacts of earlier snowmelt by delaying runoff hydrographs. At the local level, acequia system seepage supports riparian vegetation, recharges shallow groundwater, and even improves shallow groundwater quality by diluting nutrients. These local and regional hydrologic benefits of acequia systems may provide positive feedbacks that reinforce acequia community resilience. We are studying the coupled hydrologic, environmental, sociocultural and economic systems of three acequia communities that with low to high water availability to help identify these elements of resilience and clues to sustainability in the face of climate change and land use change.

#### **Ecosystem Services, Faunal Biodiversity and Vegetation Dynamics in Response to Forecasted Land-use and Climate Change within Upper Rio Grande (Boykin)**

Native vegetation dynamics and associated faunal biodiversity are affected by changes in land use and climate. Recent efforts have focused on identifying the benefits that humans derive from functioning ecosystems. As such, ecosystem services, i.e., “services provided to humans from natural systems,” have become a key issue in resource management, conservation planning, and environmental decision analysis. Mapping and quantifying ecosystem services have become strategic national interests for integrating ecology with human benefits to help understand the effects of policies and actions and

their subsequent impacts on both ecosystem function and human welfare. Some aspects of biodiversity are valued by humans, and thus are important to include in any assessment that seeks to identify and quantify the value of ecosystems to humans. Some biodiversity metrics clearly reflect ecosystem services (e.g., abundance and diversity of game species), whereas others reflect indirect and difficult to quantify relationships to services (e.g., relevance of species diversity to ecosystem resilience, cultural value of native species). Wildlife habitat has been modeled at broad spatial scales and can be used to map a number of biodiversity metrics. We have mapped metrics reflecting ecosystem services or biodiversity features using terrestrial vertebrate habitat model data from the U.S. Geological Survey Gap Analysis Program. Example metrics include species-of-greatest-conservation-need, threatened and endangered species, harvestable species (i.e., upland game, waterfowl, furbearers, and big game), total species richness, and specific taxon richness. We have evaluated the regional effects of urban outgrowth and land use change on biodiversity metrics reflecting ecosystem services in the Rio Grande Basin in New Mexico. We measured the response of these biodiversity metrics to varying scenarios of land use, climate, and population growth using the Environmental Protection Agency’s Integrated Climate and Land use Scenario (ICLUS) data cover for the period 2000–2100. Our analysis identifies areas of priority and sensitively to land-use and climate change within the Rio Grande Basin. This effort provides a unique broad scale view, but further research is necessary to understand the relationships at the 3 fine scaled watersheds associated with acequias. Tipping points for sustainability of biodiversity vary across scales and our work attempts to identify the scales at which acequias benefit biodiversity.

#### **The Acequia Model: Local Knowledge and Sociocultural Adaptation in the Northern Rio Grande Watershed Commons (Rivera)**

The mountain acequias of the northern Rio Grande are water management institutions that take surface water out of upland tributaries to irrigate valley farmlands alongside one or both sides of the stream. These human made artifacts function both as physical infrastructure for water conveyance as well as the basis of social organization in terms of water allocation, rules for governance, and the pooling of labor to maintain a communal irrigation system. In most watersheds, the acequias are the first diversions, and due to their autonomy in decision making, the acequia *mayordomos* can adapt quickly to seasonal variability in streamflow and other physical and ecosystem changes. The CNH sociocultural team conducted focus group sessions at three study sites in the summer of 2012 to probe a set of interrelated questions about system resilience in the Acequia Model: acequia governance and

water sharing customs; food crops and seed traditions; transmission of local knowledge; mutualism and social capital; land ownership and land use; and livestock grazing practices in a farm-ranch traditional economy. Our preliminary findings characterize the Acequia Model as a resilient institution that adapts to stressors in the environment largely due to factors of solidarity, attachment to land and place, and the ecological knowledge embedded in the collective memory of the *parciantes*. Of equal significance, we are also calibrating “tipping points” that threaten the functionality of the acequia as a complex biophysical, economic, ecological and sociocultural system that links valley irrigation with resources of the upland watershed. Inputs from the Acequia Model will be incorporated into the System Dynamics architecture adopted for the modeling of coupled natural and human systems within the multidisciplinary NSF CNH study. The final report will include a research monograph that analyzes the socio-ecological history and current conditions of the Rio Chama watershed utilizing qualitative and visualization methodologies.

## **Session 2**

### **Monitoring and Modeling Hydrologic Connectivity in Semi-Arid Watersheds (Ochoa)**

The hydrologic connectivity between upland water sources, floodplain valleys downstream, and groundwater may be an important determinant of hydrologic resilience in the face of climate variability. In order to better understand hydrologic interactions between uplands and associated valleys, we are using a combined field data collection and modeling approach to characterize the hydrologic connectivity of three watersheds and their associated irrigated valleys in northern New Mexico. At these study sites, we are monitoring several weather variables and different hydrologic parameters including precipitation, river and acequia discharge, soil moisture, runoff, and groundwater. Field data collected are being used to calculate water budgets at the field and valley scales and to characterize surface water and groundwater interactions in these acequia-irrigated systems. Also, these data are being used to parameterize a system dynamics model that allows expanding calculations at the field and valley scales into the watershed scale. Also, this system dynamics model allows scenario testing for different climate and population levels of disturbance. Preliminary results suggest that there is a strong hydrologic connectivity between snow-melt driven runoff in the headwaters and the recharge of the shallow aquifer in the valleys, mainly driven by the use of traditionally-irrigated agriculture systems.

### **Acequia Perspectives on Climate-Change and Population Growth and the Perspectives of Preparedness and Adaptation (Hurd)**

This study investigates local-scale adaptation and long-run capacity building in acequia communities in Northern New Mexico, where there is a long record of resilience and adaptive capacity spanning more than four centuries. These communities may be particularly vulnerable to current stresses from population growth, changing community composition, and projections of water scarcity that are expected to accompany long-run climatic changes. This paper uses a survey approach to explore factors and community characteristics that contribute to community adaptation, the level and extent of community preparedness, and the preferred community actions to cope with stresses and disturbances. Key findings suggest that land ownership and acequias’ attachment to water and community have helped these communities cope with environmental and community-based stresses. Results showed divided opinions regarding the degree of “perceived preparedness” and “perceived vulnerability” to disturbances such as population change and growth, aggressive regional development, economic hardships, and droughts.

### **Modeling the Hydrologic/Ecologic/Economic/Social Dynamics of Small Scale Community Irrigation Systems (Acequias) (Tidwell)**

Acequias, small scale community irrigation systems, have played a critical role in the settling and development of the Southwestern United States. The acequia is more than a physical infrastructure for irrigation. It is also a system of governance for managing resource allocation, and provides a point of focus for community cooperation and communication (e.g., maintenance of the ditches). These traditional systems of water management have evolved to increase community productivity as well as resilience to climate variability. Changing economies, lifestyles, and governance structures (e.g., state managed water rights) have challenged the adaptive capabilities of these communities over the last century. Projected climate change and continued urban develop could overwhelm this traditional lifestyle and with it lose the valuable ecosystem services and the cultural/social resources they provide. Our interest here is to develop a framework for understanding the physical/social/cultural dynamics governing the vitality of these acequia-based agricultural systems and the communities they support. A system dynamics architecture is adopted for modeling this multidisciplinary problem. Key system modules include upland forest management, livestock grazing, surface-groundwater hydrology, forest-aquatic ecology, agricultural practice, population dynamics, rural community economics and social networking. Key system stressors are represented by climate change and downstream urban de-

velopment. Models will be developed for three separate and different acequia systems in Northern New Mexico. These individual models will then be aggregated into an Upper Rio Grande basin wide model to assess the role of acequias on broad system health.

### **Session 3**

#### **Safeguarding Valencian Acequias: History and Values of a Millennial Water Sharing Culture (Martínez)**

The Valencian country, in Eastern Spain, constitutes a worldwide referent for acequia studies. The Valencian irrigation systems and the agrarian landscapes created by them (the *huertas*) have called the attention of local intellectuals and foreign water experts for centuries, being praised for the genius of their physical and institutional design. Besides that, acequia culture has provided the Valencian people with some of their most prominent identity symbols, such as the traditional huerta dwellings (*barracas, alquerías*), as well as the farmer's clothing and folklore. Acequia institutions have acted both as a cohesive factor for the irrigators and their local communities which frequently provide identity references, the paradigm being the Tribunal of Waters of Valencia, that itself has become a worldwide symbol of swift, equitable and fair water justice.

Paradoxically, though, this valuable water culture has not been the object of public policies from the point of view of their preservation and transmission to future generations, with very negative effects. Since the 1960s on, acequias and *huertas* have suffered impacts from urban and infrastructure development fueled by speculation, with their sequel of pollution, *huerta* landscape fragmentation, distortion and extinction. In more recent times the acequias have also been exposed to other threats, such as the ones derived from the so-called “modernization” or “improvement” of irrigation systems: a hegemonic discourse that has promoted the substitution of the traditional open air, irrigator-operated acequias by concrete and rubber irrigation pipes depending on engineering and computerized systems, with the double effect of landscape impoverishment and disempowerment of irrigators.

It has not been until very recent times, in historical terms, that a Valencian movement toward acequia safeguarding has started to develop, in the context of its identification as cultural heritage, fostered by civic platforms, committed researchers and fully aware irrigators. The paper will address the history and organizational principles of the Valencian acequias and their analysis as heritage elements, to end with a description of their current situation and future prospects.

#### **Encounters with the Moral Economy of Water: Convergent Evolution and Diffusion in Valencia (Trawick)**

The author presents the results of a long period of comparative research on successful community-managed irrigation systems in different parts of the world, work that was generously encouraged and supported throughout the years by Elinor Ostrom. Briefly comparing two systems of widely different scales and levels of complexity in the Peruvian Andes and on the Mediterranean coast of Spain, he argues that both are examples of a particular cultural model for sharing water successfully under conditions of scarcity, one that has emerged independently in a great many local settings and places throughout the world. It consists of a set of principles for allocating and using the resource that interact with and reinforce each other in a remarkable way, making it possible to manage it in an equitable, transparent, and sustainable way. This “moral economy of water” appears to have emerged to form the heart of distinct but highly similar hydraulic traditions in the Andes and in Islamic Spain, but to have spread through diffusion to other regions, being carried long ago by colonists from the Valencia region of Spain to northern Mexico and the upper Rio Grande and Colorado River basins in the New World. The “canal culture” that exists today in the Taos Valley and other parts of New Mexico appears to fit this general model, as do a great many systems in still other parts of the world, e.g., India, Pakistan, Nepal, the Philippines, and even Bali. These smallholder or “peasant” irrigation systems are largely self-organized and self-governed, but in all cases they are under threat today from a variety of causes. The author suggests that the most effective way of defending them, in New Mexico and elsewhere, is first of all to recognize, as Elinor Ostrom initially did, that they are all of a single type.

#### **Society and Hydrology in a Chilean Andean Watershed: How Poor Knowledge of the Hydrological System Produces Social Conflicts. (Arumi Ribera)**

Poor understanding of complex groundwater-surface water interactions in the Andean watershed of Chile can produce social problems and conflict. This paper presents a case study of the Diguillín River watershed, located in Central Chile. The Renegado creek is one of the main tributaries of the Diguillín watershed. The development of an important tourism center featuring thermal waters has seriously affected the valley. Land use has changed in that there are now more than 1000 vacation homes and several resorts. In the winter season the valley can receive more than 20,000 tourists, and about 5,000 in summer. However, because the Renegado creek watershed has a lower availability of water than neighboring watersheds, its potential for further development is seriously limited. Preliminary results of an ongoing research project show that the Renegado wa-



tershed is located over porous volcanic rock deposits with high infiltration rates, where water percolates to a fractured rock system and travels 30 Km until it discharges into the Diguillin river. Because this hydrological system is poorly understood, many conflicts over water availability have arisen and the future development of the Renegado valley will be highly compromised. Yet new projects are underway, including two ten-floor buildings that are going to be constructed without water. A final concern is how development of the Renegado watershed will impact the water quality of the Diguillin river, because pollutants move very quickly through the fractured system.

### **The Effects of Social and Economic Disturbances on the Taos Acequias of Northern New Mexico (Cox)**

The acequias of New Mexico and Colorado have survived for centuries using traditional water sharing practices. These traditions are currently being threatened by a suite of social, economic, and political disturbances. This talk will explore the affects of such disturbances on the acequias of the Taos Valley of Northern New Mexico. To do so, it will illustrate the results of a household survey of acequia members as well as an analysis of historical data, including remotely sensed satellite imagery data of the valley.

## **Session 4**

### **Regime Shifts in the Morning of the World (Lansing)**

It has been shown that ecosystems may undergo nonlinear responses to stresses or perturbations. Hence there can be more than one stable state or regime. Whether alternative stable states also exist in coupled social-ecological systems is an open question. We investigated responses to environmental and social challenges by eight traditional community irrigation systems (subak) along a river in Bali, to test the intuition that as a result of their different histories of local adaptation, the older and more demographically stable upstream subaks respond differently to both environmental and social challenges, and thus inhabit a different regime than downstream subaks with less stable populations. Results confirm the existence of two distinct regimes. The more resilient upstream subaks lie in a deep harmonic well, while the downstream subaks exhibit greater variation in their adaptive capacity. The minimum energy pathway between the two regimes gives probabilistic insight into transitions between two basins of attraction.

### **Visible and Invisible Self-managed Irrigation Organizations (Palerm)**

How important is a long term legal framework for irrigation system institutions? Based on a comparison between countries having a consistent long term legal framework

for self-managed irrigation systems seems to correlate with strong and visible institution, such as Spain, Japan, Chile, the US. Lack of this framework, seems to correlate with lack-of or weak irrigation institutions. At least this is the explanation arrived at by Sengupta to explain the lack of irrigation institutions in India. In Mexico, however, in spite of a changing and chaotic legal framework we find that informal or non-official irrigation institutions and horizontal agreements are in place. Some of these institutions were officially suppressed, others lost their legal framework, others never had a legal framework, and still others never received official recognition. We have found continuity for some cases dating back to XVIth century institutions as well as new organizational efforts. It would seem that rather than a lack of institutions, what we find is that the irrigation institutions and horizontal agreements are invisible.

Finding the informal organizations has been possible by asking about local arrangements on the ground, instead of paying attention to the official information and the official institutions.

What do these case studies mean? In the first place that a consistent legal framework for self managed irrigation institution allows them to be visible and probably makes them stronger and more capable of negotiating, but the legal framework is not necessary. In the second place it showcases that these institutions are very resilient and that there is an organizational capacity ready to be deployed.

The paper centers on a few examples of informal organizations.

### **Irrigation Management in Pre-Saharan Morocco: Some Perspectives from the Assag(q)yas of the Ziz Oasis (Ilahiane)**

This paper describes a community-based irrigation management system and examines how communal labor extortion shapes irrigation management in the Ziz Oasis of south-central Morocco. First, I argue that ethnicity, religion, and social power are defining elements in access to and management of land and water resources. Second, while community-based land and water management is based on social exploitation of low status groups, the system of water management has proved to be “sustainable” in managing water resources. Third, in contrast to the ecological, economic, and social goals of sustainability and policies to reverse inequality differentials in ethnically heterogeneous environments, the often mechanical association of sustainability with equity outcomes is overemphasized, and perhaps in the long run, policy makers as well as anthropologists ought to find ways to cope with the challenge of a “tolerable” level of inequity in community-based water management schemes.

## Is the Crafting of Self-Governing Irrigation Institutions in the XXth Century Following Elinor Ostrom's Principles Still Relevant in the Beginning of the XXI Century? (Ruf)

In the 1980s Wittfogel's theory of Oriental Despotism continued to provide a popular explanation for hydraulic development. In these same years, under the influence of neoliberalism, there emerged the idea to put a halt to heavy planning of hydraulic systems and make water into a market commodity. The 1992 Dublin Conference on Water and the Environment is the symbolic moment of this turnabout. In the same year, however, Elinor Ostrom took an alternative stance to the prevailing theories on the development of irrigation.

To highlight Ostrom's contribution and its limits, we studied and compared the principles that underlie the three theories of the social, economic and political organisation of irrigation. In this triangular confrontation, Ostrom contributes several useful keys to analyze on-going conflicts in the 21st century. Out of this theoretical profusion there can emerge a practice of action-research to solve current conflicts over water resources.

This contribution is inspired by an article published in the French scientific review *Nature Sciences Sociétés* in 2010, when Elinor Ostrom came to Montpellier and to Unesco in Paris. It will be illustrated by stories on irrigation system development in the Andes and in the Mediterranean Basin.

## GLOSSARY

### A

**Acequia:** An irrigation network of traditional, gravity-fed, usually unlined irrigation canals and ditches that are managed by the community that surrounds it.

**Acequia association:** Consists of farmer-rancher parcientes and landowners who are obligated to pay dues, contribute labor to the cleaning and maintenance of acequia infrastructure, observe the customary principles of water sharing, and annually elect a mayordomo and three commissioners who oversee ditch management and governance. Parcientes in an association share a presa into a hand-dug acequia madre from which venitas channel water to individual properties.

**Acequia capital/moral economy:** A stable economy based on goodness, fairness, and justice in which participants cooperate and avoid economic free-rider problems as well as manage environmental externalities like soil erosion, flooding, or wildfires.

**Acequia de común:** "Commons ditch."

**Acequia madre:** Main canal or "mother ditch."

**Acequia outflow:** Large amounts of water that remain unused from agricultural demands and exit at the end of the acequia.

**Adaptive capacity:** Term that characterizes the flexibility, amount of available resources, and capability to adjust in a timely and effective fashion to some change or disturbance.

**Agropastoralists:** Members of a group that live by a mixture of agriculture and livestock herding.

**Agua es vida:** "Water is life," a saying that reflects the feeling of collective identity and strength through connectedness of life to water.

**Alcalde:** "Mayor"; also a town in Northern New Mexico where New Mexico State University's Sustainable Agriculture Science Center is located.

**Alternative futures:** Multiple scenarios created based on differing decisions and outcomes (climate and development scenarios) to perspectives provided to decision makers based on those different potential outcomes.

**Los ancianos:** "The elderly."

**Aquifer recharge:** Water that moves from the land surface or unsaturated zone into the saturated zone.

**Arreglos:** Operational rules that were specific to the water delivery requirements of the shared canal and its laterals.

**Auxilio:** "Assistance"; multiple ditches that share diversions during droughts or other emergencies; emergency water. More commonly, the term refers to a special dispensation water a parciante requests from the mayordomo during extreme scarcity, usually to water livestock or keep a garden alive.

**Ayuda mutua:** "Mutual help" for survival.

### B

**Balancing (or negative) feedback process:**

When the causal relationships self-correct one another such that growth or decay is hindered or offset by another force.

**Baseflow:** Streamflow in between storms or runoff events that is maintained by groundwater contributions.

**Biodiversity:** The healthy populations of many different species of plants and animals; the variety of life in the world or in a particular habitat or ecosystem.

**Biodiversity metrics:** Species richness datasets based on species habitat models that reflect a portion of biodiversity or some type of ecosystem service.

**Bosque:** “Woodlands”; a type of gallery forest habitat found along the riparian flood plains of stream and riverbanks in the southwestern United States.

## C

**Camino Real de Tierra Adentro:** “Royal Road of the Interior Lands.”

**Caminos de agua:** “Water roads”; acequia watercourses that extended settlements along the Camino Real de Tierra Adentro.

**Causal links:** The visual creation of feedback loops that are specified with a “+” or “–” sign depending on the cause-and-effect relationship.

**Causal loop diagrams (CLD):** A visual schematic or map illustrating the systemic connections between variables.

**Cequier:** Head water official in the acequias of Valencia, Spain.

**Chain referral method:** A method that consists of finding and contacting a household that meets at least one of the target population criteria, and then individuals are asked to help identify and introduce researchers to other individuals with similar characteristics or from the same subgroup of the population.

**Cofradías de Penitentes; cofradía:** Religious brotherhoods where Catholic men associated for purposes of religious worship, rituals of penance during Holy Week, and to help others by performing various, specific acts of charity.

**Commissioners:** The secretary, treasurer, and president who, in concert with the mayordomo, oversee all ditch business.

**Commons:** A cultural or natural resource that is accessible to all members of a society and is held in common rather than privately owned.

**Community resource management:** Research by Elinor Ostrom who documented small, local communities that share resources, such as forests, pastures, and water, and that over time develop rules to share and care for the resources.

**Community science:** One of the most effective approaches to science that creates new understanding on problem solving by looking to the community for identification of critical issues and provides a two-way conduit of information.

**Compadrazgo:** The reciprocal relationship or the social institution of a relationship; the institution of designating and enacting the roles of compadres/comadres.

**Compadres:** “Friends”; fictive kin, for example god parents to one’s child or those who witness/sponsor a marriage.

**Compuertas:** Headgates on acequias that take water into parcientes’ individual parcels.

**La comuna:** The basic irrigation unit in Valencia, Spain, that distributed water, maintained the canal system, and elected a cequier to administer the ordenanzas of the canal.

**Confianza:** “Reciprocal trust.”

**Congreso de las Acequias:** New Mexico annual meeting of acequias by the non-profit New Mexico Acequia Association.

**Connectivity:** The dynamic linkages that operate across a range of physical and social phenomena and scales that are amenable to quantitative and/or qualitative approaches.

**Consejo de vecinos:** “Council of neighbors/citizens”; the early town government in New Mexico history.

**Consumptive use:** Water that is lost from the system and is no longer in a usable form.

**Coupled natural-human systems:** See **Dynamics of coupled natural and human systems**.

**Cuarentas:** Acreage of rangeland awarded to Hispanic settler families that was intended to provide sufficient forage to sustain a dairy cow or to occasionally grow dryland crops.

**La cultura de ayuda mutua:** “Culture of mutual-self-help.”

## D

**Deep percolation (DP):** Movement of water below the roots of crop plants; the total amount of water percolating below the root zone.

**Desagüe:** “Drainage”; outlets, turnouts, or sluices on the acequia that return tailwaters from an acequia to the river.

**Devisas:** Membership ribbons used by mutual aid societies.

**Día de San Ysidro:** Feast days for the village patron saint of San Ysidro on May 15th (also spelled San Isidro).

**Días de fatigas:** Daily labor responsibilities during the annual cleaning of the acequia.

**Dynamics of coupled natural and human**

**systems; dynamics of coupled natural and human systems program (CNH):** The National

Science Foundation program that granted an award to the coauthors of this book; the scientific understanding of integrated socio-environmental systems and the complex interactions (dynamics, processes, and feedbacks) within and among the environmental (biological, physical, and chemical) and human (“socio”) (economic, social, political, or behavioral) components of such a system. The coupling expresses that the human and nature components should no longer be considered or treated as separate, isolated entities.

## E

**Ecosystem integrity:** The system’s capacity to maintain structure and ecosystem functions using processes and elements characteristic for its ecoregion.

**Ecosystem services:** The goods and services from ecological systems that benefit people.

**Ejidos:** “Common lands”; commons for use by all villagers for livestock grazing, hunting, and other uses.

**Environmental capital:** Indispensable resources and benefits, essential for human survival and economic activity, provided by the ecosystem; also known as “natural capital.”

**Eutrophication:** Excessive algal or plant growth.

**Evapotranspiration (ET):** The process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants.

## F

**Feedback loops:** Loops in system dynamics that either create growth (or decay) or act to self-correct the behavior of a system. Visually they are created using causal links.

**Field capacity:** Amount of water the soil can hold when excess water has drained out.

## G

**Gaining stream:** A stream that gains water from subsurface flows.

**Groundwater return flow:** When water is diverted from a river, seeps into the ground, and then eventually returns to the river system.

## H

**Hermanos:** “Brothers”; members of Cofradías de Penitentes.

**Huertos:** “Orchards.”

**Hydrograph:** Graph showing the rate of flow (discharge) versus time past a specific point in a river, channel, or conduit carrying flow.

**Hydrologic budgets:** Budgets that account for inputs and outputs of water in a defined region, such as a field, farm, valley, basin, or even an entire state.

**Hydrologic services:** The subset of ecosystem services related to water.

**Hydro-social cycle theory:** The conceptual bridge for blending natural and social scientific perspectives to demonstrate that water is social.

## L

**Leverage points:** According to system dynamics, places in a system’s structure where a small change can lead to significant and lasting results.

**La limpia de las acequias; la limpia:** Annual spring cleaning of the ditches in preparation for irrigation.

**Linderos:** Laterals on the acequia.

**Losing stream:** A stream that loses water into the ground because the water table is below the bottom of the stream channel.

## M

**Mancomunidad:** A union of citizens; communal labor.

**Matachines:** Traditional dance portraying the triumph of Christianity performed in Hispanic villages and some Indian Pueblos.

**Mayordomo:** Ditch manager; ditch boss.

**Mercedes de tierra:** Spanish land grants.

**Milpas:** “Fields.”

**Moradas:** Private chapels that also served as meeting halls for the Cofradías de Penitentes; Penitente chapter-houses.

**Moral economy model:** A system of principles and values that supports and guides cooperative, independent economic practice.

**Mutualism/mutualismo:** Mutual aid; the social capital of a community that fosters a relationship of interdependence based on mutual trust and reciprocity for the common good; the collective well-being expressed by members of the community.

## N

**Novena:** A Catholic tradition of devotional praying consisting of private or public prayers repeated for nine successive days or weeks.

**De nuestro pueblo:** “From our community”; core belief of each mutual union that help should come from the people in the community, all for the good of the society and advancement of the common welfare.

## O

**Obras de caridad:** Local projects of charity developed by the sociedades mutualistas.

**Ojito:** “Water spring.”

**Ordenanzas:** “Rules.”

## P

**Parciantes:** Member irrigators on an acequia.

**Penitentes:** Members of a morada, also referred to as hermanos.

**Pobladores:** “Settlers.”

**Pobladores principales:** Settlement leaders when petitioning for a land grant.

**Presa:** Stream diversion.

**El pueblo:** “Town.”

## Q

**Querencia:** What anchors people to the land. This attachment informs and inspires mutualism across neighbors and kin who live in the same place.

## R

**Reinforcing (or positive) feedback process:** When the causal relationships create unencumbered growth or decay.



**Repartimiento:** Customary division of water along the ditch; water schedules; water sharing agreements.

**Repartimiento de tierras:** Land partitions in a land grant.

**El reparto:** Short for repartimiento, or the customary division of water within an acequia or between acequias on a stream system during times of scarcity.

**Respeto:** “Respect.”

**Riegos ancestrales:** “Ancestral irrigation systems.”

**Riparian ecosystems:** Ecosystems that are associated with streams, rivers, and other bodies of water or are dependent on the existence of perennial, intermittent, or ephemeral surface or subsurface water drainage.

**Riparian habitats:** The interface between land and a river or stream.

## S

**Saca de agua:** Digging out of the ditch.

**San Ysidro/San Isidro:** The patron saint of farming.

**Sangrias:** See **Linderos**.

**Seepage:** Process by which water slowly leaks into the soil.

**Seepage conveyance losses:** The slow movement of some of the water into the bed and banks of a canal, ditch, or acequia.

**Sensitivity analyses:** A form of model testing by changing the original model assumptions.

**Sobrantes:** Surplus or leftover water to be used by an agreed upon ditch or second party.

**Social capital:** A capital of connections, honorability, and respectability related to but distinguishable from economic and political capital.

**Sociedades mutualistas:** “Mutual aid societies”; a lay version of the Cofradías de Penitentes who added new forms of mutual aid to what the Cofradías had developed, such as offering low-cost life insurance, providing economic assistance in times of illness, granting small loans, and, in some cases, combatting wage and racial discrimination of workers in the railroad, mining, and other resource extractive industries.

**Solar:** Small privately owned parcel of land on the non-irrigated side of an acequia granted to Spanish settler families to build their homes.

**Species rich areas:** Areas where more species are predicted to occur.

**Stocks-and-flows:** Represent areas of material accumulation and methods of transfer or movement. Primarily these are used for physical goods or quantities, but they can also be applied to sources of information or qualitative features.

**Suertes:** Farm tracts allocated to land grant petitioners for agricultural use.

**Surface water return flows:** Field and acequia tailwater that goes directly back to the river.

**System dynamics (SD); system dynamics**

**model; system dynamics modeling:** A methodology for studying complex systems that provides an intuitive and informative way to display how multifaceted connections operate within these systems. It places priority on decision-making processes and mental models of stakeholders to understand a system’s behavior over time. The process ends with the completion of a quantitative model capable of testing hypotheses that aren’t easily addressed by models within a single disciplinary framework.

## T

**Turbidity:** Cloudiness of water.

## U

**Upland habitat:** The area of the watershed that does not receive regular flooding by a stream.

## V

**Vecinos:** “Neighbors”; a term used to refer to early Nuevomexicano settlers or citizens.

**Vegas:** “Pastures.”

**Venitas:** See **Linderos**.

**Vicious cycle:** Activities or processes that reinforce an initial unfavorable change into a potential continuous breakdown or detrimental results.

**Virtuous cycle:** Activities or processes that reinforce or support an initial favorable change into continuous improvement or favorable results.

## W

**Water balance method:** The water flow into and out of a system.

**Water budget:** An accounting of all the water that flows into and out of a defined area; also known as hydrologic budget.

**Water table fluctuation method (WTFM):** A method to determine aquifer recharge based on groundwater level rise and the specific yield of the aquifer.

## Z

**Zanjas:** Earthen canals.

## COAUTHOR BIOGRAPHIES

**Guillermo Alvarez** is currently an ecology and evolutionary biology doctoral student at the University of Texas at El Paso, with a focus on communities of lizards and snakes of the Chihuahuan Desert. He obtained an M.S. in conservation ecology and an M.S. in plant and environmental science from New Mexico State University. His graduate research included investigations in water conservation strategies, the bioclimatic envelope of parthenogenetic whiptail lizards (*Aspidoscelis* spp.), and toxicity studies on a federally listed Chiricahua leopard frog (*Lithobates chiricahuensis*). Guillermo's ultimate goal is to continue research in herpetofauna ecology and conservation in desert biomes.

**Kenneth G. Boykin** is an Associate Professor and ecologist with the Center for Applied Spatial Ecology in the Department of Fish, Wildlife, and Conservation Ecology at New Mexico State University in Las Cruces. He is also director of New MexicoView, a consortium of members and institutions that are committed to the advancement and dissemination of remote sensing technology in New Mexico. Ken received his B.S. in biology from NMSU, his M.S. in biology from Texas Christian University in Fort Worth, and his Ph.D. in rangeland resources from NMSU. His research interests include conservation, habitat modeling, riparian ecosystems, fire ecology, herpetology, and amphibian declines.

**Andrés F. Cibils** is a Professor of Rangeland Science in the Department of Animal and Range Sciences at New Mexico State University in Las Cruces. He teaches undergraduate and graduate courses in arid land management and grazing ecology. Andrés and his graduate students conduct research on animal-plant interactions, focusing specifically on the foraging behavior of rangeland-raised livestock. He collaborates with researchers in Argentina, Chile, Mali, Mexico, Mongolia, Scotland, and Uruguay, and has volunteered in farming communities in Central America and West Africa. Andrés received his B.S. in animal science from Universidad Nacional de Lomas de Zamora, Buenos Aires, and his M.S. and Ph.D. from Colorado State University in rangeland ecosystem science.

**Lilian Cibils** is an Assistant Professor in the School of Teacher Preparation, Administration and Leadership (TPAL) in the College of Education at New Mexico State University. She holds a Ph.D. in curriculum and instruction from NMSU, an M.A. in foreign languages and literatures from Colorado State University, and a B.A. in literary and technical scientific translation from the Instituto de Enseñanza

Superior en Lenguas Vivas, J.R. Fernández, Buenos Aires, Argentina. Her research focuses on qualitative inquiry in multilingual contexts, linguistically and culturally responsive teacher education, and diverse definitions of parent involvement in family-school relations. She teaches graduate courses, such as qualitative research methods, as well as undergraduate courses in the areas of teaching English as a second language (TESOL) and bilingual education within the teacher education program. Her book *Immigration, Motherhood and Parental Involvement: Narratives of Communal Agency in the Face of Power Asymmetry* was published in 2017 and is based on the findings of a qualitative case study.

**Alexander G. "Sam" Fernald** was the principal investigator for the Coupled Natural and Human Systems Project from which this book stems. He is a Professor in the Department of Animal and Range Sciences at New Mexico State University and director of the New Mexico Water Resources Research Institute (NM WRRI). His primary research interests include water quality hydrology; land use effects on infiltration, runoff, sediment yield, and nonpoint source pollution; effects of surface water/groundwater exchange on water availability and water quality; and coupled natural and human system approaches to water sustainability for communities and ecosystems. Dr. Fernald received a Fulbright Scholarship to Patagonian National University, Trelew, Argentina, in 2008, and another Fulbright Scholarship to the University of Concepcion, Concepcion, Chile, in 2000. He has authored and coauthored numerous peer-reviewed articles, book chapters, and technical reports. As director of the NM WRRI, he leads the Institute in its mission to develop and disseminate knowledge that will assist the state, region, and nation in solving water resources problems. Dr. Fernald's earned degrees include a B.A. in international relations from Stanford University, an M.E.M. in water and air resources from Duke University, and a Ph.D. in watershed science from Colorado State University.

**Steven J. Guldán** is superintendent of New Mexico State University's Sustainable Agriculture Science Center at Alcalde, and Professor of Agronomy in NMSU's Department of Plant and Environmental Sciences. His research covers vegetable, fruit, and forage crops, and hydrology of acequia systems. He received the 2016 José Fernandez Memorial Chair to continue his research of developing year-round, intensive, high-value production systems using high tunnels. Steve received his B.S. in geography from Minnesota State University in Mankato and his M.S. and Ph.D. in agronomy from the University of Minnesota.

**Brian H. Hurd** is a Professor of Agricultural Economics and Agribusiness at New Mexico State University. He earned a B.A. in economics and environmental conservation from Colorado University in Boulder and a Ph.D. in agricultural economics from the University of California–Davis. He uses methods and approaches that emphasize the connectedness of natural and human-managed systems—such as water, climate, food, energy, and environment—to study how communities mitigate and adapt to possible adverse effects of climate disruption and environmental change. Recognized internationally as an expert in the economics of climate change impacts and adaptation on water and agricultural resources, Brian has lectured and served in various countries, including Mexico, Thailand, Cambodia, Tunisia, Spain, Senegal, Saudi Arabia, the Philippines, Australia, and Italy. He has served on the board of directors and as president of the Universities Council on Water Resources (UCOWR). He is a member of several organizations, including the Agricultural & Applied Economics Association, Western Agricultural Economics Association, American Water Resources Association, and Association of Environmental and Resource Economists.

**Stephanie C. López** is a former graduate research assistant in the Department of Animal and Range Sciences at New Mexico State University. Stephanie received an M.S. in range science, and her thesis focused on the role of livestock in suppressing rangeland weeds and sustaining traditional agropastoral communities in Northern New Mexico. Stephanie excelled as a graduate student at NMSU, receiving the New Mexico Higher Education Graduate Fellowship and the Alvin L. and Lorena P. Neumann Memorial Endowed Scholarship. Shortly after graduation, Stephanie and her husband moved to the Midwest. Stephanie is currently a full-time parent.

**Laura Mayagoitia** received her B.A. in international relations from Tecnológico de Monterrey, Campus Chihuahua, Mexico, and her M.S. in agricultural economics from New Mexico State University. She worked as a rural development consultant in the municipalities of Bachiniva and Cuauhtémoc, Chihuahua. She also worked with Ecología y Polación, a Mexican non-profit, supporting several small-scale agriculture demonstration centers in Latin America. Currently, she is collaborating with the Living Lab/Centro de Diálogo y Transformación Inc., located in Chihuahua, on a collaboration of sustainable projects.

**Carlos G. Ochoa** is an Associate Professor of Ecohydrology and Integrated Watershed-Riparian Systems Management at Oregon State University. His research includes investigating surface water-groundwater interactions, ecohydrologic connections, aquifer recharge, and land use-water quality relationships in arid and semiarid rangelands in northern Mexico and Oregon, as well as in the more humid agricultural landscapes of western Oregon. Carlos received his B.S. in animal and rangeland sciences from Universidad Autónoma de Chihuahua in Mexico and his M.S. in agricultural economics and Ph.D. in range science (watershed hydrology) from New Mexico State University.

**José A. Rivera** is Professor Emeritus at the School of Architecture and Planning and serves on the research staff of the Center for Regional Studies at the University of New Mexico. He holds degrees in the humanities, a master's in social welfare, and a Ph.D. in social policy from Brandeis University. After graduating from Brandeis, he spent most of his academic career at the University of New Mexico teaching in graduate programs within the fields of public administration, community and regional planning, and an interdisciplinary degree program in water resources. In the area of research and scholarship, he is known for his books and journal articles related to acequia irrigation from a comparative and multidisciplinary perspective, with a focus on governance and social organization. Field work sites have included Mexico, Spain, Peru, the Philippines, and the Upper Rio Grande in the United States. Major works include a coauthored book published by Island Press in 1991, *Rural Environmental Planning for Sustainable Communities*, followed by *Acequia Culture: Water, Land and Community in the Southwest* (University of New Mexico, 1998), *La Sociedad: Guardians of Hispanic Culture Along the Rio Grande* (University of New Mexico, 2010), and a translation of his first book, *La Cultura de la Acequia*, published by the University of Valencia in 2009.

**Sylvia Rodríguez** is Professor Emeritus of anthropology and former director of the Ortiz Center for Intercultural Studies at the University of New Mexico. She has also taught at Carleton College and the University of California–Los Angeles. Sylvia's research and publications have focused on interethnic relations in the Upper Rio Grande Valley of New Mexico, where over the past three decades she has studied the cultural impact of tourism, ritual and ethnic identity, and conflict over land and water. Her award-winning publications include two books, *The Matachines Dance: Ritual Symbolism and Interethnic Relations in the Upper Rio Grande Valley* and *Acequia: Water Sharing, Sanctity, and Place*. Sylvia received her B.A. in anthropology from Barnard College and her M.A. in anthropology and Ph.D. in anthropology-psychology from Stanford University.

**Adrienne J. Rosenberg** is the editor at the New Mexico State University Sustainable Agriculture Science Center in Alcalde. She received her bachelor of arts and sciences for global studies with a focus in culture and society at The University of Tennessee in Knoxville and received her master's in international human rights with a certification in humanitarian aid at the University of Denver. She has been an agrarian in Northern New Mexico for eight years and has owned and operated her former mushroom business, Woven Web Farm. Her audio documentary business, Ecotones, focuses on the intimate relationships between people and their landscape, in particular the acequias of New Mexico, and she is a consultant for her business, Woven Web Design, on restoration habitat building for pollinators on land connected to acequias. She was honored to work alongside the brilliant minds and hearts behind this book and contribute toward acequia culture and the residents/parciantes of New Mexico.

**Elizabeth A. Samson** received her B.S. in geography and natural resource environmental science from Kansas State University. During her undergraduate studies, Elizabeth worked as a research assistant for the KSU Department of Biology on the Ramps Long Term Research Project. She also worked for the U.S. Department of Commerce as a geographic specialist performing demographic statistics. She received her M.S. in wildlife science from New Mexico State University. As a graduate student, Elizabeth was a research assistant in the Applied Spatial Ecology Lab under Dr. Kenneth Boykin. She then worked as a biologist for several architecture/engineering private firms. Currently, Elizabeth works for the United States Army Corps of Engineers on large-scale conservation and planning projects as well as military installations.

**Ursula R. Smedly** received her B.S. in fisheries and wildlife from Michigan State University and her M.A. in agricultural extension education from New Mexico State University. Ursula was a wildlife research assistant with the San Antonio Mountain Elk Project with the New Mexico Cooperative Fish and Wildlife Research Unit of NMSU. She was the natural resource agent with the Rural Agricultural Improvement and Public Affairs Project based out of NMSU's Sustainable Agriculture Science Center in Alcalde, New Mexico. From 2008 through 2012, Ursula was the Extension Natural Resource Specialist for NMSU, where she provided educational programming and technical assistance regarding timber, wildlife, fire, water, and range to 13 north-central New Mexico counties. In 2007, she was awarded the Agent Achievement Award by the Association of County Agricultural Agents.

**Vincent C. Tidwell** is a Distinguished Member of the Technical Staff at Sandia National Laboratories. He has over 20 years of experience conducting and managing research on basic and applied projects in water resource management, nuclear and hazardous waste storage/remediation, and petroleum recovery. Most recently, his efforts have focused on establishing a multi-agency, multi-university center devoted to the creation and application of computer-aided decision support tools and stakeholder-mediated decision processes. The focus of this effort is on water resource management and planning. These models adopt a system dynamics framework for integrating the broad physical and social processes important to water planning. Additionally, these system-level models are directly linked to a variety of other tools, providing an integrated basis for analysis, visualization, and decision support. Vince earned a B.S. in geology from the University of Texas at Arlington and an M.S. in hydrology and water resources at the University of Arizona in Tucson. In 1999, Vince earned his Ph.D. in hydrology from the New Mexico Institute of Mining and Technology.

**Benjamin L. Turner**, Ph.D., is currently an Assistant Professor of Natural Resource Management at Texas A&M University at Kingsville where he is responsible for developing an interdisciplinary research program focusing on contemporary natural resource management problems, leading and teaching the undergraduate agribusiness and ranch management programs, and serving alongside faculty in the King Ranch® Institute for Ranch Management. Originally from Normangee, TX, Ben received a B.S. in agriculture from Sam Houston State University in 2009. He then received an M.S. in agribusiness with an emphasis in ranch management from Texas A&M University at Kingsville in 2011. He also worked briefly for an energy company and an agricultural bank. In 2014, he completed a Ph.D. in natural resource management from South Dakota State University, where he worked on grassland, soil, and water conservation issues. After completing his dissertation, Ben worked as a post-doctoral researcher at New Mexico State University as part of an interdisciplinary team examining the ecosystem goods and services provided by acequia communities in Northern New Mexico. Outside of the university, Ben is a member of the Society of Range Management, the Soil and Water Conservation Society, and the System Dynamics Society. He lives in south Texas with his wife, Viviana, and son, James.



## NOTES

This image shows a single sheet of white paper with horizontal ruling lines. The lines are evenly spaced and run across the width of the page. There are no margins, text, or other markings on the paper.

## This image shows a single sheet of white paper with horizontal ruling lines. The lines are evenly spaced and run across the width of the page. There are no margins, text, or other markings on the paper.

## NOTES

This image shows a single sheet of white paper with horizontal ruling lines. The lines are evenly spaced and run across the width of the page. There are no margins, text, or other markings on the paper.

The College of Agricultural, Consumer and Environmental Sciences is an engine for economic and community development in New Mexico, improving the lives of New Mexicans through academic, research, and Extension programs.

Contents of publications may be freely reproduced, with an appropriate citation, for educational purposes. All other rights reserved. For permission to use publications for other purposes, contact [pubs@nmsu.edu](mailto:pubs@nmsu.edu) or the authors listed on the publication. New Mexico State University is an equal opportunity/affirmative action employer and educator. NMSU and the U.S. Department of Agriculture cooperating.