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Connectivity of Coupled Hydrologic and Human Systems as the Basis of Resilience in Traditional Irrigation Communities in New Mexico

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Abstract. Changes in land use and water availability are impacting the integrity of traditional irrigation systems and their associated communities worldwide. We designed a study to quantify the components of resilience within coupled hydrologic and human systems in New Mexico USA. We worked collaboratively with three communities in the northern Rio Grande basin to characterize hydrologic, ecological, socio-cultural, land use, and economic system components of linked water and human social systems. Building on component models and quantified resilience examples, we crafted graphical representations of connectivity and resilience. We added data points from around the world gleaned from a research workshop. We found there was more hydrological connectivity with flow paths from irrigation system to irrigated field to groundwater and river; the most important nexus was shallow groundwater recharge. There was more human connectivity with strong connections to land and community involvement; an important nexus was mutualism/social capital. Within the northern New Mexico communities, it appears that hydrological connectivity is associated with higher water availability and even if disconnected due to water scarcity can be restored with renewed water availability. Community connectivity, on the other hand, seems susceptible to long term disruption that self-perpetuates long after the initial stresses are imposed. We compared resilience of the hydrologic and human systems on axes of climate (arid to sub-humid), hydrologic connectivity (between surface water and groundwater and between watershed and river), and community connectedness (between water users and water infrastructure and between community members and water management organizations) including communities from northern New Mexico, Bali, Spain, Morocco, central Chile, Mexico, Ecuador, and southern New Mexico. Hydrologic connectivity was most related to local water availability and climate. Community connectivity seemed to be a function of other variables such as mutualism and local control of governance. Changes in water availability and land use affected communities disproportionately. There appears to be a combination of characteristics that has particularly high resilience: medium aridity allows enough water for hydrologic connectivity yet has enough water scarcity to engender collective community action. Promoting connectivity may be a way to enhance resilience of traditional irrigation communities.

Keywords: Connectivity, resilience, coupled natural and human systems

1 Introduction

New Mexico's acequia or traditional community irrigation systems have never before been so studied, so organized on a regional level, so celebrated and advocated, or so close to extinction, as they are today. As small-scale farming and ranching declined over the decades following World War II and rural, land-based New Mexicans turned increasingly to wage or salaried employment outside the agricultural sector, acequia irrigation has concurrently diminished. Urban and real estate development, demographic change, water-right transfers, an escalating water market, water-right adjudications, drought, and climate change all contribute to the challenges that threaten traditional irrigation practices, water governance, and the physical infrastructure of acequia communities.

Yet, despite these mounting challenges, acequias and traditional irrigation tenaciously persist into modern times. And despite--or perhaps because of--water market pressure, plus attrition in traditional practices and local knowledge, acequia associations have formed ever larger coalitions to help combat the myriad forces of extinction. Acequia activism and acequia scholarship have raised awareness about the historical significance, adaptive value, and sociocultural importance of the agropastoral subsistence pattern that took shape along the northern Rio Grande basin of New Mexico during the 17th, 18th, and 19th centuries. Today, scholars from research institutions around the U.S. as well as abroad come to investigate various aspects of community acequias.

At the forefront of current acequia research, a team of New Mexico university researchers and acequia organizations is collaborating on the scientific study of the hydrology, ecological adaptation, agricultural economy, and sociocultural character of the community irrigation systems. The goal of this National Science Foundation funded interdisciplinary project is to understand acequia-moderated linkages between culture and nature and to quantify survival tipping points. Accordingly, the study investigates and seeks to characterize the role of acequias in hydrologic buffering, community resilience, and ecosystem health. This ambitious study strives to integrate, within a single conceptual framework, the hydrologic acequia linkages between surface water and groundwater in river valleys and contributing watersheds in upland environments with the socioeconomic and cultural features of acequia communities that function to increase ecosystem resilience to climatic and socioeconomic stressors.

2 The Northern New Mexico Case: 1598 to 2014

From the time of first Hispanic settlement in the northern Rio Grande, a jurisdiction defined as the *Río Arriba* in colonial New Spain, 1598-1821, hydrologic function and social organization in the valley bottomlands have been inextricably linked to the uplands bioregions in the *sierras* of the Sangre de Cristo and other mountain ranges (Rivera and Martínez, 2009a). Water supply was the key to settlement policies under the 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. The typical land grant was conveyed from among the *tierras realengas* to towns and communities and were referred to as *tierras concegiles* to be owned and regulated by a *consejo* or town council as *ejidos* (Meyer and Brescia, 1998). The *ejido* proper held much of the surrounding resources in common for grazing of livestock in open meadows and pastures, gathering of building materials and firewood from forested lands, and also for hunting and fishing in the streams (Gonzales, 2003).

Once these lands were conveyed in a formal possession ceremony by the Provincial Governor or the district Alcalde, 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 y su justicia*, a council of neighbor/citizens as selected by them 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 mutual aid, *mutualismo*, 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).

As a complement to the *ejido* lands, each settler was also granted farm tracts or *suertes* on which to build a house (*solares*) 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 date. This process of *repartimiento de tierras* (land partitions), executed by the Governor or the Alcalde, was repeated by the landowners themselves when it came time to build and then administer the acequia system, running through the community from the *atarque* constructed by hand from local natural materials of timber and boulders, through the *acequia madre*, usually one on each bank of the river, and into the *desagüe* or drain as return flow to the river. This form of cooperative mutual aid was a constant process of making social arrangements across the landowner *vecinos*, such as devising plans (*el reparto*) to distribute and share water, elect *mayordomos* and other officials, establish rules for water allocation, resolving internal conflicts and disputes, and also 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.

2.1 Hydrologic Connectivity: Surface and Groundwater

A major objective of the NSF interdisciplinary research study is to examine the factors that make for acequia sustainability while at the same time probe into "tipping points" that could destabilize the system, whether physical or social, or both. We find that the community acequias of the northern Rio Grande have survived more than four centuries and seem to have created the conditions for their own "self-perpetuation," referring to their ability to adapt to changes in climate, economic structures and other influences (Ortiz, 2014). A fundamental aspect of acequia system sustainability is water availability. Acequia systems in northern New Mexico are heavily dependent on spring runoff from snowmelt in the southern Rocky Mountains (southern Colorado and northern New Mexico). Expected climate change scenarios in the southwestern USA call for severe and more persistent drought conditions and that includes higher temperatures and a reduction in snowpack. This could greatly affect the amount and time when runoff water will be available for acequias to use. Less water and a change in the time when it is available can substantially modify cropping patterns and water management in these agroecosystems; this can turn into a "tipping point" for the sustainability of acequias in northern New Mexico. Therefore, it becomes critical to better understand the hydrology of acequia systems and determine potential risks and ways of adaptation and mitigation under more severe water scarcity conditions.

The hydrologic connectivity between upland water sources and acequia irrigated valleys and between surface water and groundwater flows can be an important factor of hydrologic resilience. Precipitation, runoff and infiltration processes in the uplands are directly associated with stream and groundwater flows reaching the acequia irrigated valleys. Acequias in northern New Mexico are typically located in alluvial floodplains along the main rivers and creeks and overlie relatively shallow aquifers. In many cases, this allows for relatively rapid interactions between surface water and shallow groundwater sources resulting in irrigation seepage contributions to the local aquifer and return flow to the river.

In an effort to gain insight into the hydrologic connectivity between upland water sources and acequia irrigated valleys downstream, we are conducting intensive field data collection and modeling research in three different acequia systems. These three acequia valley/watershed systems (El Rito, Rio Hondo, and Alcalde) are representative of, relatively, low, medium, and abundant water conditions that are commonly found in the northern part of New Mexico. Ongoing field studies and modeling efforts out of these three sites have provided critical understanding of hydrologic connectivity and surface water and groundwater interactions. For instance, results from the Alcalde study site showed a significant increase in river stage (0.3 m) in response to runoff contributions from a higher elevation precipitation event that generated peak flows of 17.9 m^3 s^{-1} at a tributary ephemeral stream (Fig. 1). In addition, the presence of perched water systems found in the uplands of this study site is an indicator of surface water and groundwater connectivity (Ochoa et al., 2013). At these three study sites, part of the streamflow from the snowmelt period is driven during spring and summer into the acequia conveyance system and distributed for irrigation throughout the floodplain valley. Surface water and groundwater connections in the acequia agricultural valleys follow a seasonal pattern, driven by increases in river flows and by acequia and irrigation seepage inputs to the local aquifers. Fig. 2 shows data from a well located next to the Acequia de Alcalde, at a fair distance from the river and from any irrigated field, indicating that this well is being recharged primarily by acequia seepage. Fig. 3 shows data from a well located in the core of the Rio Hondo valley where higher water table fluctuations observed seem to respond to a combination of augmented river flow and irrigation seepage conditions. Seepage from acequias and flood irrigation applications continuously percolates to the shallow aquifer, where it is temporarily stored, and then returns via shallow groundwater flow back to the river (Fernald et al. 2010).

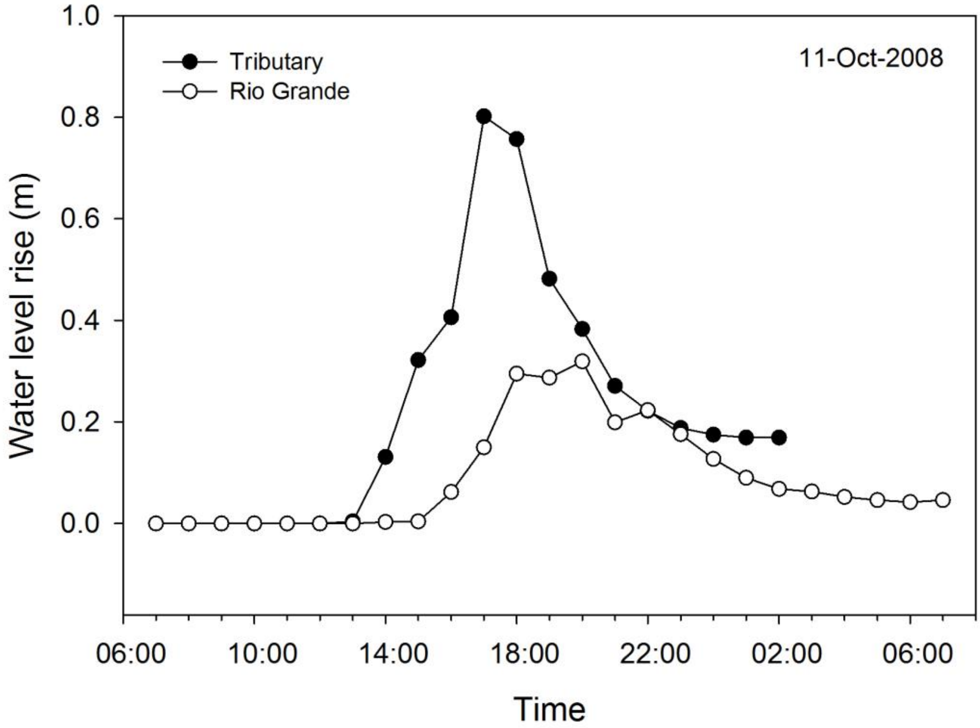

Fig. 1. Tributary and river stage response to rainstorm on 11 October 2008 at the Alcalde site (Figure published in Ochoa et al., 2013).

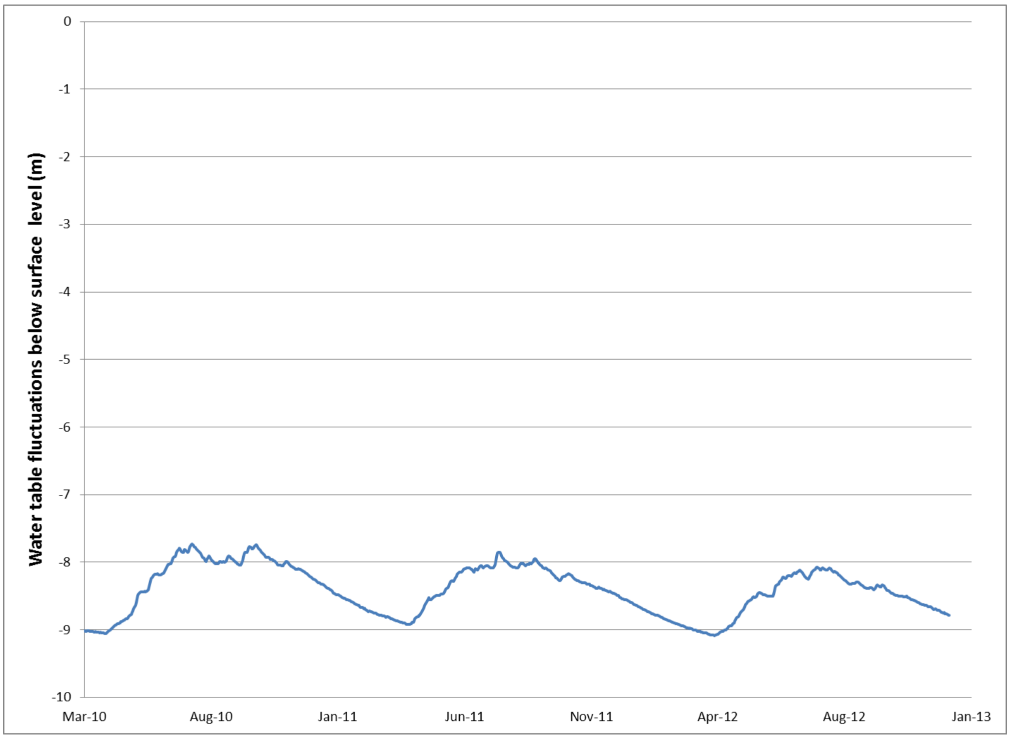

Fig. 2. Seasonal water table response in one well at the Alcalde site.

Fig. 3. Seasonal water table response in one well at the Rio Hondo site.

As part of our ongoing modeling effort, we are parameterizing a system dynamics model that will enable us to simulate different hydrologic interactions taking place in these acequia valley/watershed systems. In particular the model will simulate how changes in climate, land use, and vegetation management, can impact surface and groundwater connectivity in acequia systems. In addition, the model also attempts to describe how changes in water availability can impact the downstream ecosystem, and economics and traditional culture of the acequia communities.

2.2 Sociocultural Connectivity: Community Adaptations

On the practical side, we examine the acequia experience through temporal and spatial lenses. Historically, we know that the acequia *pobladores* were challenged in the Laws of the Indies, plus, more importantly, the aridness of the region, to observe the natural systems around them and from there devise plans on how to divert the natural streams, channel water into *madres* and *sangrías*, level land to plant and grow crops, and extend the riparian landscape, thus making agriculture possible in a snowmelt basin. In the history of early settlements along the Rio Grande, that is why people were recruited to come to this region, and why they chose to do so--the incentives of land, and with land, water to irrigate and grow crops. This meant modifying the natural systems and included building of homesteads in the *solares*. They modified the environment, but the technology of gravity flow meant that there were inherent physical limits, let alone the need to sustain these resources season to season. They took the surface water they needed when flows were sufficient, and during drought, shortages were shared. As a basic principal, the environment, or natural systems, shaped what they could do or not do. Lastly, settlement morphology and land use followed a dispersal pattern, always in search of snow pack watersheds of the Rio Grande and its tributaries in the uplands.

Geographically, each site was different, since this irrigation technology conformed to the topography, hydrology, and soil conditions locally in every valley bottomland, mostly tight canyons within small watersheds. Acequias are positioned at the outlets of snowmelt basins, divert water from a river and utilize gravity flow to irrigate agricultural fields. When acequias were being established, the variations in local topography dictated each acequia's uniqueness along with a social structure and its related social arrangements. In time, the acequia as a social system implanted itself into the hydrological cycle for community subsistence, the main economy, and became the defining structure of the local ecosystem (Ortiz, 2014). Each of these locales would then require unique institutional arrangements that would work, and these were devised by way of "*arreglos*" within each collective of *vecinos*, such as the *repartimiento* for the distribution and sharing of water. This same geography is also subject to changes in the hydrocycle year to year, meaning that the social arrangements too need to change accordingly, such as adaptations made during drought cycles. Over time, a set of customary practices evolved rooted in ecological knowledge of the landscape and transmitted generation to generation.

2.3 The Acequia Hydro-Social Cycle

The NSF study in the northern Rio Grande basin has begun to delve more systematically into the interaction and connectivity between the acequias as both a physical and a human organization with reference to the emerging paradigms of the "hydro-social cycle" (Fig. 4). On the physical side, the acequias serve as water diversion and delivery systems that need to be repaired and maintained from time to time. The acequia is a key water management institution, and often has the most upstream diversion on mountain rivers close to the snowpack in the forest, a critical natural water storage system that slowly releases water as spring run-off at the start of each irrigation season. In the conceptual model for the NSF research study (Fernald et al., 2012), the acequia is at once a physical and social system, that lies at the center of hydro-social renewal, or as Linton would describe "a social-natural process by which water and society make and remake each other over time and space" (Linton, 2014). Linton and other proponents of the hydro-social cycle have challenged the foundational modern premise that nature and humans/society are separate and distinct. They argue that nature/society dualism clouds the analysis of particular, or historically and geographically situated, hydro-social systems (Linton and Budds, 2013; Linton, 2014; Schmidt, 2014).

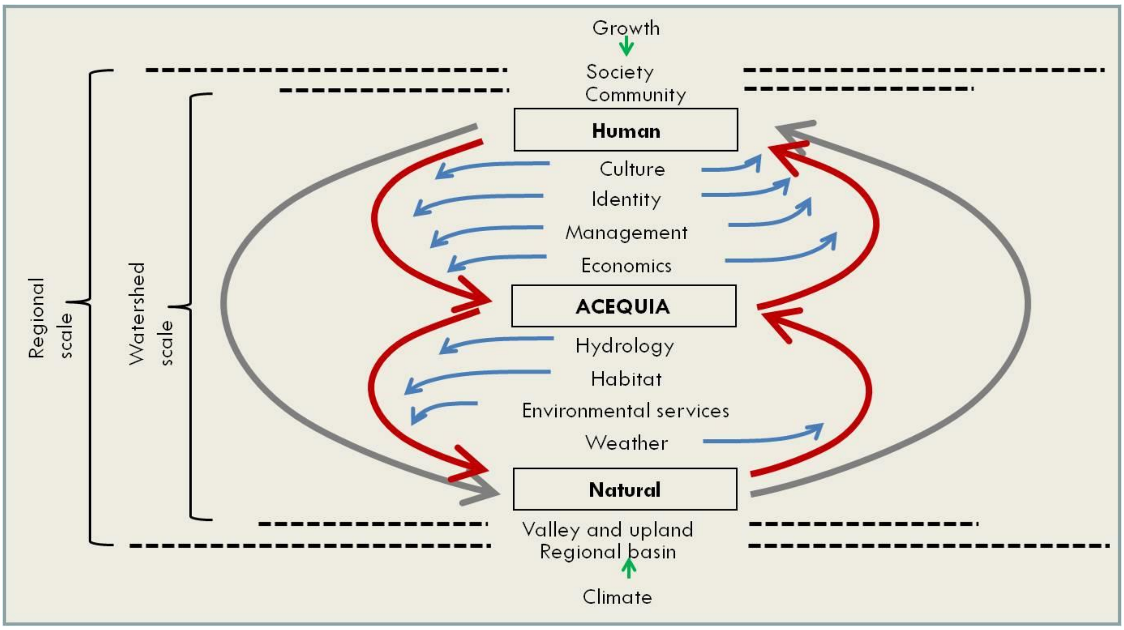

Fig. 4. Schematic depicting the acequia at the center as a Human Organization and Physical Infrastructure (from Fernald et al., 2012).

Based on preliminary results from the NSF research, we propose to define the hydro-social cycle in this manner: the modern concept of the hydrological cycle sees water as a natural process unto itself, above and apart from the human domain. The hydro-social cycle, on the other hand, emphasizes that water is inseparable from a human and social context, a connectivity that self-perpetuates system resilience. The acequia hydro-social cycle in New Mexico places the abstract scheme of the hydrological cycle within a specific human cultural landscape, a watershed ecosystem that includes acequias. The snowpack in the winter coupled with precipitation generated by storm clouds in the summer months provide runoff that feeds valley streams, groundwater and acequias. The acequia diversions in turn make human settlements possible by use of flood irritation that also recharges local aquifers or groundwater in an integrated watershed ecosystem. Water is diverted only when available in a cycle of renewal at the start and within each irrigation season with an adaptive capacity to modify rules for water distribution and the sharing of shortages unique to each locale.

If the hydrological cycle is universal and everywhere, the hydro-social cycle is integral to a particular geographic location, time, and social arrangement. In the context of acequias of New Mexico the hydro-social cycle is synonymous with or produces a unique waterscape, a mosaic or *paisaje del agua* of value to the region and society as a whole. This human modification produces a greenbelt extending the riparian zone of the river, creating an oasis that sustains habitats for plant biodiversity and wildlife native to the region, while recharging the aquifer and returning surplus water to a *desagüe* channel for reutilization by other stakeholders downstream. The acequia landscape includes the *presa*, *acequia madre*, *partidores*, *compuertas*, laterals or *sangrías* to the fields, *canoas* or aqueducts, flumes, culverts, and in some communities *ojitos* (springs), *tanques* (storage ponds), *molinos* (gristmills), and terraces. In addition, there are structures or landmarks in the built environment associated with the history and evolution of acequia settlements: fences, corrals, barns and sheds, bridges, foot paths or *caminos* along the acequia, *capillas* (churches), *moradas* (penitent chapels), *camposantos* (graveyards), *calvarios* (hilltop crosses), and homesteads of vernacular architecture (Rodríguez, 2006; Rivera and Martínez, 2009b). Data from the New Mexico study points to a strong factor of human connectivity linking land, water and attachment to community as place. In turn, the traditional system of water governance is based on mutualism/social capital as an important nexus for adaptation and resilience.

2.4 Connectivity and resilience

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 (Fig. 5). 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.

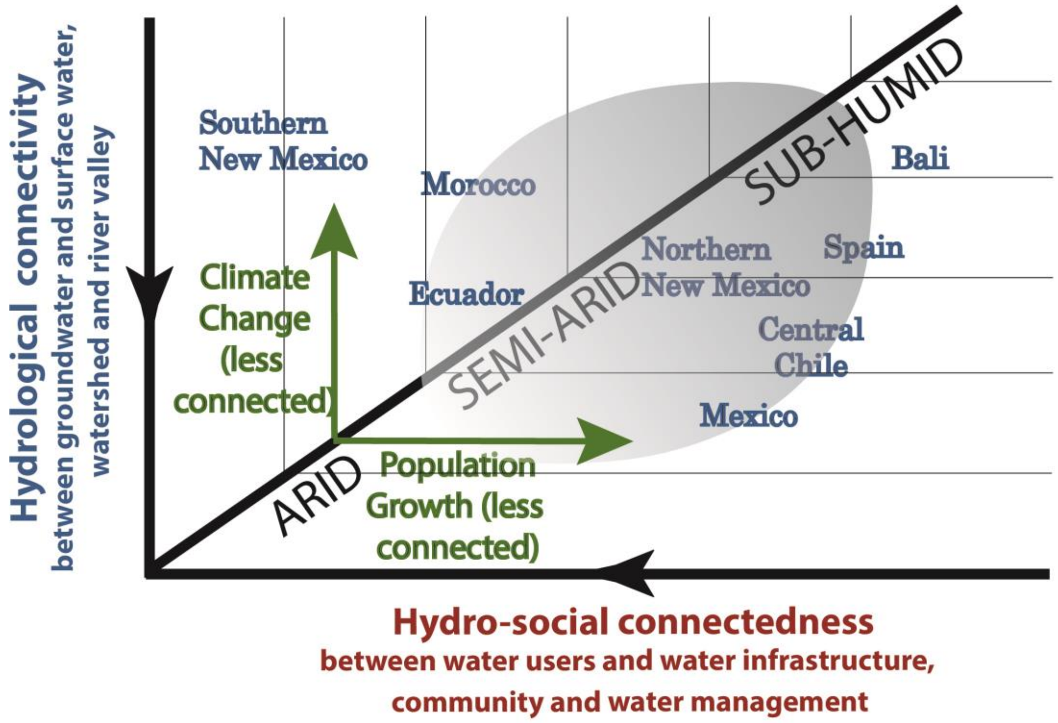

Fig. 5. Conceptual diagram of the relationship between resilience and hydrologic connectivity and hydro-social connectedness.

A confluence of conditions appears to exist in semi-arid systems that is particularly resilient, as depicted by the gray shaded space in Fig. 5. 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

3 Conclusions

In our investigation of the hypothesis that connectivity between hydrologic and human aspects of traditional acequia irrigation systems of New Mexico has formed the basis for their resilience to date, we conclude the following.

- Hydrologically, seepage recharges groundwater and provides connectivity through attenuated return flow to rivers and streams.
- Community connectivity seems to be a function of variables such as mutualism and local control of governance.
- Attachment to place derived from acequia and local farming culture provides community cohesion and resilience.
- Traditional local knowledge about the hydro-social cycle of acequia operations is a key factor in acequia resilience.
- Acequia systems have remarkable resilience and adaptive capacity, but also show susceptibility to major upheaval. Thus, external drivers such as climate change and population growth that impact water and ties to the land are particularly disruptive.
- There appears to be a combination of characteristics that has particularly high resilience: medium aridity allows enough water for hydrologic connectivity yet has enough water scarcity to engender collective community action.
- Promoting hydrologic and hydro-social connectivity may be a way to enhance resilience of traditional irrigation communities.

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References

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(2):195-233.

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, *J. Irrigation Drainage and Eng.*, 136:823-835.

Fernald, A., V. Tidwell, J. Rivera, S. Rodríguez, S. Guldan, 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.

Gonzales, P.B. (2003): Struggle for Survival-The Hispanic Land Grants of New Mexico, 1848-2001, *Agricultural History*, 77(2):293-324.

Linton, J. and J. Budds (2013): The hydrosocial cycle: Defining and Mobilizing a Relational-Dialectical Approach to Water, *Geoforum,* Elsevier article in press. Accessed on April 24, 2014: http://dx.doi.org/10.1016/j.geoforum.2013.10.008

Linton, J. (2014): Modern Water and Its Discontents: A History of Hydrosocial Renewal, *WIREs Water*: 1:111-120. Accessed on April 24, 2014: *WIREs Water* 2014, 1:111–120. doi: 10.1002/wat2.1009

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*, 73:321-345.

Ochoa, C.G., S.J. Guldan, A. Cibils, S. Lopez, K. Boykin,V.C. Tidwell, and A.G Fernald (2013): Hydrologic Connectivity of Head Waters and Floodplains in a Semiarid Watershed, *Journal of Contemporary Water Research and Education*, 152:69–78.

Ortiz, Q. (2014): Acequias as a Sustainable Model for Hydro-Ecology, *Green Fire Times* 6(1):23.

Rivera, J.A. con traducción de Luis Pablo Martínez (2009a): *La Cultura de la Acequia: Agua, tierra y comunidad en el Suroeste de los Estados Unidos de América*, Universitat de València.

Rivera, J.A. and L.P. Martínez (2009b): Acequia Culture-Historic Irrigated Landscapes of New Mexico, Unpublished paper presented at The Contribution of the Commons: The effect of collective use and management of natural resources on environment and society in European History, Pamplona-Iruñea.

Rodríguez, S. (2006): *Acequia: Water Sharing, Sanctity, and Place*, School of Advanced Research Press, Santa Fe, New Mexico.

Schmidt, J.J. (2014): Historicising the Hydrosocial Cycle, *Water Alternatives*, 7(1):220-234. Accessed April 24, 2014: www.water-alternatives.org

Van Ness, J.R. (1991): *Hispanos in Northern New Mexico-The Development of Corporate Community and Multicommunity*, AMS Press, New York.