Developing a System Dynamics model to investigate sustainability of traditional acequia communities of New Mexico

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Abstract: Agriculture-based irrigation communities of northern New Mexico, forms of Coupled Natural-Human and Common Pool Resources systems, have survived for centuries despite the arid environment in which they reside. These irrigation communities provide a broad array of ecosystem goods and services, which are being threatened by regional population growth, urbanization, gentrification, economic development, climate change, and other factors. System dynamics modeling provided an interdisciplinary platform in which to investigate the sustainability of these unique systems. First, we describe the background and context of acequia communities in northern New Mexico and the challenges they face. We then develop a Dynamic Hypothesis capturing the endogenous feedbacks driving acequia community erosion. It is hypothesized that as community erosion accelerates due to forcing function variables (described above), ecosystem goods and services delivered to local and regional stakeholders will weaken. We then describe the major stock-and-flow components of the model and evaluate early calibration efforts against existing data. We find these early model results conform well to existing data and structure and provide a well-grounded platform for future model testing.

Keywords: acequia, irrigation, New Mexico, dynamic hypothesis, model development, calibration, evaluation

1. Introduction

Agriculture-based communities of northern New Mexico have survived for centuries despite the challenges of the arid environment in which they reside. This has been achieved through a system of community managed irrigation systems, called acequias [derived from Arabic as-sāqiya, meaning water conduit] brought to the region by Spanish colonists (Ackerly 1996). The term acequia refers to both the gravity-based systems of diverting river water to agricultural fields as well as to the social organizational structure of community-based water management (Mayagoitia et al. 2012). Such systems have been described as coupled natural human (CNH) systems (Fernald et al. 2012), where sustainability is rooted in the connectivity between the natural and human elements within a system, as well as common pool resource (CPR) systems (Cox and Ross 2011), where resources are managed by decentralized user-groups.

As a CNH system, watershed function and community sustainability are directly linked by acequia irrigation channels, which diverts water throughout the river valley and provides human (e.g., domestic water), agriculture (e.g., crop irrigation and livestock water), ecologic (e.g., riparian habitat support), and hydrologic benefits (e.g, enhanced surface water-groundwater connectivity; aquifer recharge; Fernald et al. 2007; Fernald et al. 2010). As a CPR, acequia water is distributed according to rules and customs passed down through the generations and supported by collective knowledge and sense of place imbedded within community members (Rodriguez 2006; Rivera 1998). This connectivity of people, land, and water is vitally important for the survival of both people and the landscape, as the "success of landscape management practices [are] ultimately determined by engagement of society in working towards sustainable environmental futures" (Brierly et al. 2006). Historically, traditional acequia communities maintained high engagement levels through two mechanisms. First, families were directly supported by agricultural activities both in the acequia and surrounding uplands, which provided timber, grazing for livestock, and hunting and fishing opportunities. This connectivity between people and land and water facilitated the development of a common *querencia* (i.e., place of the heart), which reinforced sense of place and traditions of acequia culture. Secondly, costs of leaving the community were extremely high due to proximity to basic resources in surrounding region, which made emigration a risky proposition.

Today, however, the sustainability of acequia communities face many challenges - including climate change, demographic shifts and gentrification, increasing needs for economic relief, pressures for economic development, urbanization in the surrounding region, and threats from downstream users to deliver more water (Mayagoitia et al. 2012). Agricultural production can no longer support the desired standard of living, and increasing urbanization in northern New Mexico has provided economic opportunities outside the traditional community structure. Demand for rural land continues to grow as wealthy individuals from urban cities continue to buy land for telecommuting or retirement purposes, resulting in agricultural and community fragmentation. Less acequia water diversions for agriculture can hinder the delivery of ecosystem goods and services (e.g., groundwater recharge; riparian habitat) but, more importantly, endanger the basic operations of the system itself. Despite these forces, acequia members have maintained a sense of place and remain optimistic about sustaining the traditional acequia systems (Mayagoitia et al. 2012) and have organized new institutions to support acequia sustainability (e.g., the New Mexico Acequia Association founded in 1990).

Previous investigations into acequia management have taken a variety of approaches. Much recent work has focused on acequia hydrology, including surface water-groundwater interactions (Fernald and Guldan 2006), deep percolation and shallow groundwater levels (Ochoa et al. 2007), water movement through the vadose zone during irrigation (Ochoa et al. 2009), and effects of hydrology on riparian habitat and agroecosystem functions (Fernald et al. 2007). Other approaches have focused on acequia preparedness for climate change or community restructuring (Mayagoitia et al. 2012), or the economics related to acequia participation, alternative water sources, and land fragmentation impacts on acequia resilience (Cox and Ross 2011). Interdisciplinary systems approaches (Fernald et al. 2012) have focused on identifying connections between hydrology, ecology, community, and economics.

The objective of this work is to document the development and evaluation of a system dynamics (SD) model capable of examining the sustainability of acequia communities and the economic and ecologic goods and services they provide. The SD approach was adopted as it is particularly designed for complex problems that express organized complexity (Weinberg 1975) and evolve over time (for full methodological considerations, see Sterman 2000). This approach has been used in other water related research projects (Tidwell et al. 2004; Stave 2003; Khan et al. 2009; Shanshan et al. 2010; Ewers 2005; Nandalal 2003) and is valuable for engaging stakeholders and enhancing communication and management of the problem issue at hand (Stave 2002; Winz et al. 2009; Van den Belt 2004; Tidwell and van den Brink 2008). In this paper, we first outline the acequia community study areas. Second, we describe their structure, behavior over time, and the development of our Dynamic Hypothesis. Then the SD model is presented, along with the strengths and weaknesses its exhibits based on early diagnostic tests for model confidence. Lastly, we discuss the future research aims of this SD model as well as the context in which it can be used to engage stakeholders to explore alternative adaptive measures for acequia communities in northern New Mexico.

2. Acequia locations, description and context

Communities that were established and continue to practice acequia-based management are located throughout New Mexico and southern Colorado (Figure 1), with the majority being in northern New Mexico. These communities lie along the upper and middle Rio Grande basin, including portions of the Rio Chama, Rio Santa Cruz, Taos valley, upper Pecos basin, Albuquerque, and El Paso regions (Ackerly 1996). These systems generally flow south toward Mexico and Texas with the majority of discharge originating from snow-pack in the mountainous watershed reaches. Acequia communities generally lie in small, narrow valleys ("ribbons of green") just below the mountains or along the tributary system that discharges to the Rio Grande corridor. A check dam, or *presa*, allows water to flow from the stream into the *acequia madre* (or "mother ditch"). Community members can then access the acequia through smaller *sangrias* used to irrigate agricultural fields. Any unused water at the end of the *acequia madre* flows through an arroyo or the *desague*, returning unused flow to the river source from which it came. This distribution of streamflow on the flood plain provides ecologic, economic, and hydrologic benefits (e.g., agriculture; riparian habitat; groundwater recharge) through the coupled natural-human system of the acequia.

As a CPR management systems (Cox and Ross 2011), community members along a common acequia madre, known as *parciantes*, elect three *comisionados* and a *mayordomo*. *Comisionados* (or commissioners) are tasked with accounting for individual *parciantes* contribution to ditch maintenance and negotiating water disputes with neighboring acequias, etc. A *mayordomo* (meaning steward or "ditch boss") is required to manage the annual ditch cleaning and maintain water flow in the ditch during irrigation season, approximately March through October. *Parciantes* are responsible for contributing labor to ditch cleaning and maintenance activities as well as the *mayordomo*'s salary. This social organization creates opportunities for *parciantes* to be actively involved in acequia community issues and to build cohesion and reinforce the importance of acequia function that serves as the lifeline of the community.

To take advantage of existing instrumentation and networks of local expertise, study sites were selected to build on sociocultural and hydrologic research studies already completed (e.g., Ochoa et al. 2007; Ochoa et al. 2009; Mayagoitia et al. 2012). Strong community relationships have been developed at three detailed study sites: Rio Hondo, a tributary to the Rio Grande main stem; El Rito, a tributary to the Rio Chama; and Alcalde, which is on the main stem of the Rio Grande (Figure 1). These sites are excellent for testing regional connections between the Albuquerque urban area on the Rio Grande downstream and the rural study sites upstream.

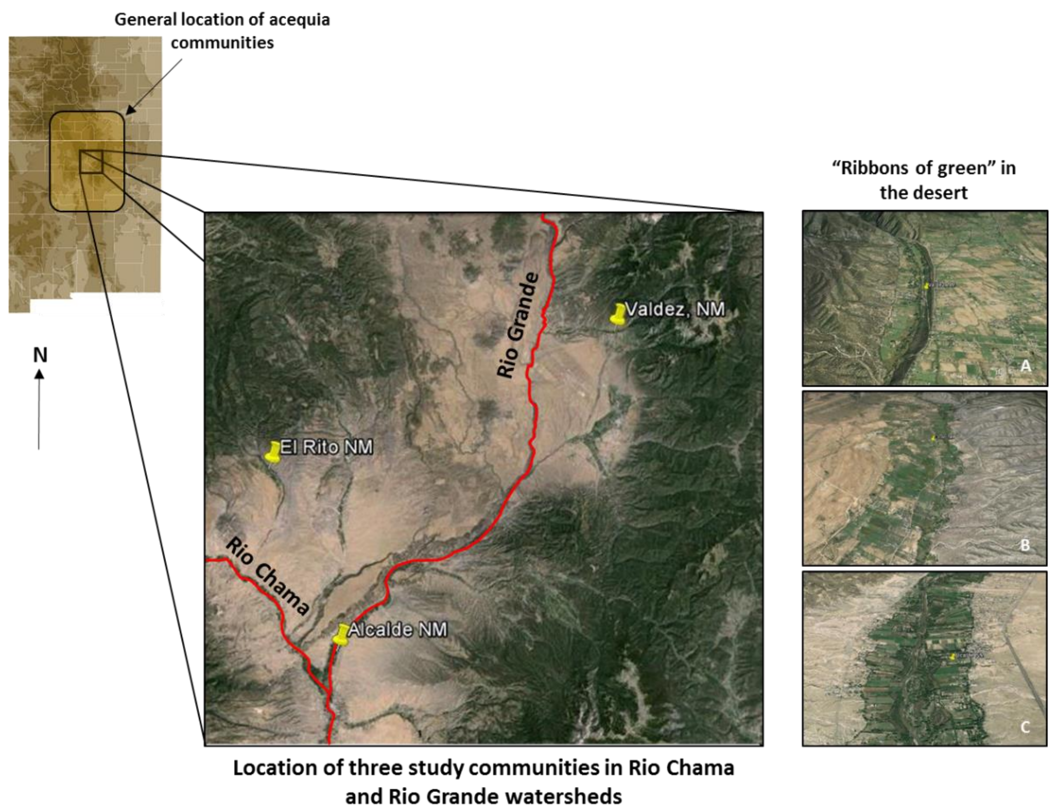

Figure 1. Location of acequia region within Colorado and New Mexico, USA, and the three study communities in northern New Mexico. Panel images A (Valdez), B (El Rito), and C (Alcalde) show the vegetative landscape, or "green ribbons", that persist in the arid region due to acequia water management.

2.1 Problem articulation

Like many arid and semi-arid regions worldwide, acequia communities are threatened in multiple ways, including: growing and changing populations; need for economic relief; pressures for greater economic development; threats of diminished water deliveries from upstream users; and threats from downstream users to deliver more water (Mayagoitia et al. 2012). Increasing population has accelerated urbanization (Figure 2), which has increased water demand and pressured acequia irrigators to sell water rights to growing urban centers downstream where demand exceeds supply (Jackson et al. 2001). Climate-change forecasts also predict that warmer and drier conditions will exacerbate historic drought occurrences (Leung 2005), which will likely increase both surface and groundwater demands.

Urbanization has also increased economic opportunities for the region (Figures 3 and 4), which has contributed to land use change within acequia communities through fallowing agricultural land in order to commute to urban centers for employment. Children have moved off the land in search of higher-paying jobs, often times never to return. As land prices have risen, and with limited private land available for residential development, residential expansion has primarily occurred on agricultural land, further reducing the already small farms within these river valleys (Table 1; Ortiz et al. 2007). With urbanization has come economic opportunities outside acequia communities, many of which have greater income potential than agriculture. Many parciantes have sought work outside the acequia in order to remain financially stable. By commuting to urban centers for work, less time is allocated to agricultural work and more land is fallowed (i.e., taken out of production). Likewise, livestock inventories that graze the watersheds above the acequia communities are reduced. Over time, fewer parciantes have been involved in seasonal acequia management activities, which threatens the foundation of this unique community structure.

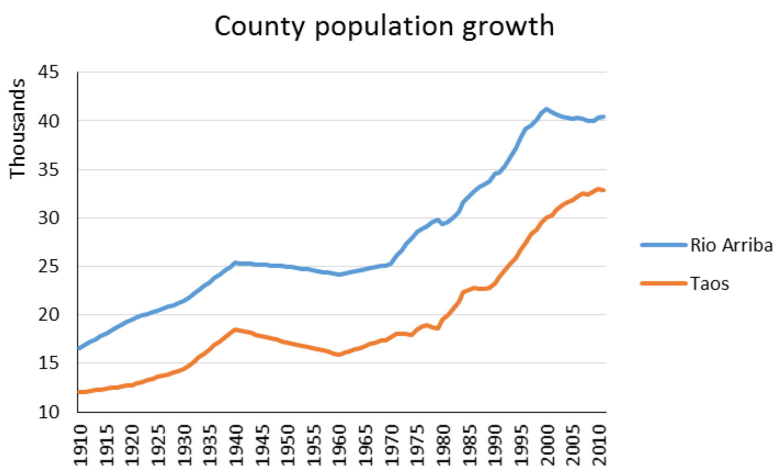

Figure 2. County population for Rio Arriba and Taos counties, where the three study communities reside.

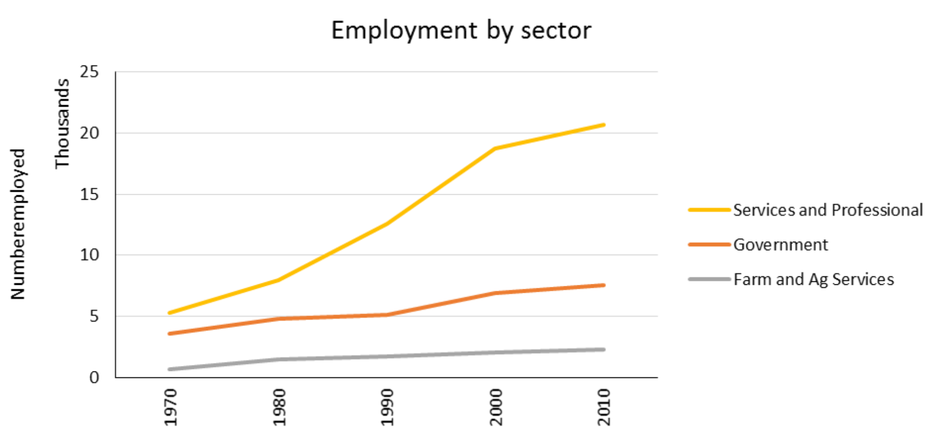

Figure 3. Combined employment figures for Rio Arriba and Taos counties over time.

Figure 4. Mean wage rates ($ job^{-1} year^{-1}) for Rio Arriba and Taos counties over time.

Table 1. Land use change in Alcade, NM acequia. Similar trends in residential increases are believed to exist in El Rito and Valdez, although the mix of reduction rates in agricultural land uses will likely differ based on unique characteristics inherent in each community. From Ortiz et al. 2007.

Alcalde, NM land use change (ha)

Land use	1962	1997	2003	% Change
Orchard	117.08	40.63	35.73	-69%
Row Crop	168.03	83.97	78.10	-53%
Fallow	N/A	6.07	6.03	0%
Pasture	170.86	246.01	251.67	47%
Riparian	176.81	154.71	170.17	-3%
Residential	56.29	258.79	367.78	533%

3. Material and methods

We used System Dynamics (SD) methodology to integrate the social, economic, ecologic, and hydrological connections that interact within an acequia community. This relies on systems thinking, which is the ability to generate understanding through engaging in mental model-based processes (Nandalal and Simonvic 2003) of the system in question. Insights gathered by engaging stakeholders (Mayagoitia et al. 2012) were enhanced by supplementing expert knowledge from various perspectives of the research team, to align community insights with physically-based processes (Fernald et al. 2012). This method has been used in previous water-related projects (as described above) and is supported by systems-based methods in ecology and natural resource management (Deaton and WInebrake 2000; Grant et al. 1997; Ford 2009). Below we outline the SD process we applied to model development, beginning with the dynamic hypothesis (DH) and building up to a working model.

3.1 Dynamic hypothesis

The DH is a working theory of how the problem of interest arose and should provide an explanation of the dynamics of the problem in terms of endogenous feedback and model structure (Sterman 2000). This working theory aims to explicitly articulate how structure and decision processes create the observed behaviour of the system (Lane 1999; Oliva 2003).

The problem being modeled is the relationship between community structure and resource management in traditional acequia communities of northern New Mexico. Acequia communities were built on common-pool resource management practices through the sharing of land and water for agricultural production, collective-knowledge transmission to future generations, and mutualism imbedded within community cooperation and sense of place. However, community mutualism has been eroding over time due to changing demographics and agricultural participation rates, which threatens the sustainability of acequia management systems (Figure 5). Our dynamic hypothesis is that this problem is driven by three factors. First, land segmentation by intergenerational division of land among children has reduced farm size and profitability, forcing land owners to seek higher wage jobs outside the community and spend less time on agricultural and acequia-related activities. Second, successful intergenerational land transfers maintain familial community ties, but often delays agricultural activities until inheritors return to the land. Third, increasing demand for land and water, coupled to the above threats, promote resources being sold or moved out of agriculture in favor of other uses (e.g., residential development; water sent to downstream users), which further segments the community (Figure 6). Consequently, acequia functions are neglected, which threatens the delivery of economic (e.g., agricultural products) and ecosystem goods and services (e.g. provisioning of water; biodiversity in riparian and aquatic habitat; etc.) it provides. Despite these forces, self-organization of remaining community members has worked to enhance political and economic position, helping to protect acequia functions and tradition.

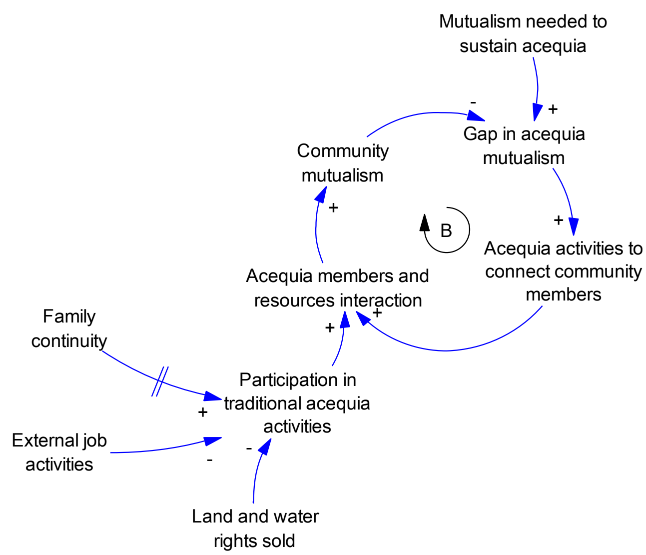

Figure 5. Causal loop diagram of community mutualism (A “+” on the arrow connecting two variables indicates the variable at the tail causes a change in the variable at the head in the same direction. A “-” would indicate a change in the opposite direction. The “B” at the center of the loop indicates it is a balancing feedback loop, in which a change in one variable feeds back to correct or stabilize the initial change) Historically, mutualism has been maintained by acequia management activities that connect acequia members with each other and natural resources, but this has slowly eroded due to low participation levels.

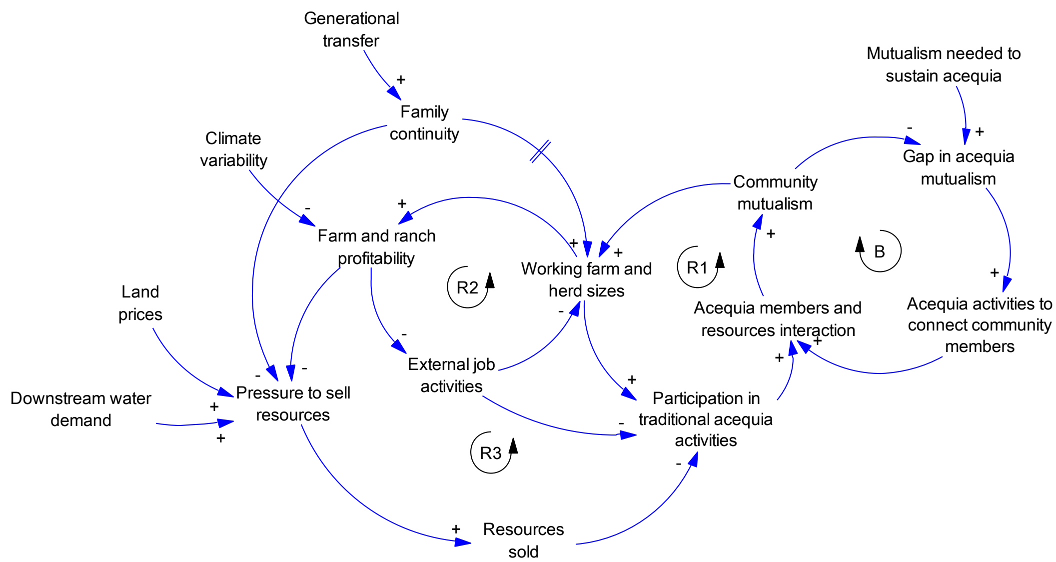

Figure 5. Causal loop diagram of the endogenous feedbacks and driving variables that contribute to low levels of participation in traditional acequia activities (The "R" at the center of the additional loops indicate reinforcing loops, in which changes in one variable feedback to perpetuate or accelerate the initial change).

The remainder of the paper describes the model, its behavior and evaluation to reference modes that generate confidence for future experimental work investigating acequia resilience.

3.2 SD model overview

The SD model incorporates economic, social, and hydrological perspectives, which operate over a fixed land base owned by acequia parciantes. Endogenous components include land, land use and time management decisions of parciantes, and community population dynamics. Exogenous components include labor wage rates, commodity prices and production costs, and climate inputs such as precipitation, snowfall, and annual temperature fluctuations, which drives stream flow and crop production systems and ultimately agricultural profitability. The model was formulated using object-oriented commercial software package, PowerSim Studio™ V. 10, using a monthly time-step over a 40 year simulation horizon (1970-2010). The same basic model structure was utilized for all three acequia communities; however, each acequia is represented by community-specific initial conditions, rate functions, etc. Below we provide descriptions of each model component. A full list of model variables and equations are provided in the Supplementary Material.

3.3. Stock-and-flow structures

3.3.1. Acequia land

Acequia land is divided into three stocks: land in agricultural production, fallow land, and residential land. Land can be transferred between production and fallow depending on management decisions and subject to delays for discontinuing or preparing for production activities. This includes changes based on agricultural economics and time management, land use change due to land sales, and intergenerational transfers of agricultural property, which are coupled to rural community dynamics. As land is developed to accommodate community growth, transfers are made from agricultural production and/or fallow land stocks to the residential stock (Figure 6). The residential stock acts as a sink where land no longer transfers use. Transfers between agricultural production and fallow land are driven by the amount of time parciantes devote to production activities and land sales, which are driven by economic and community dynamics.

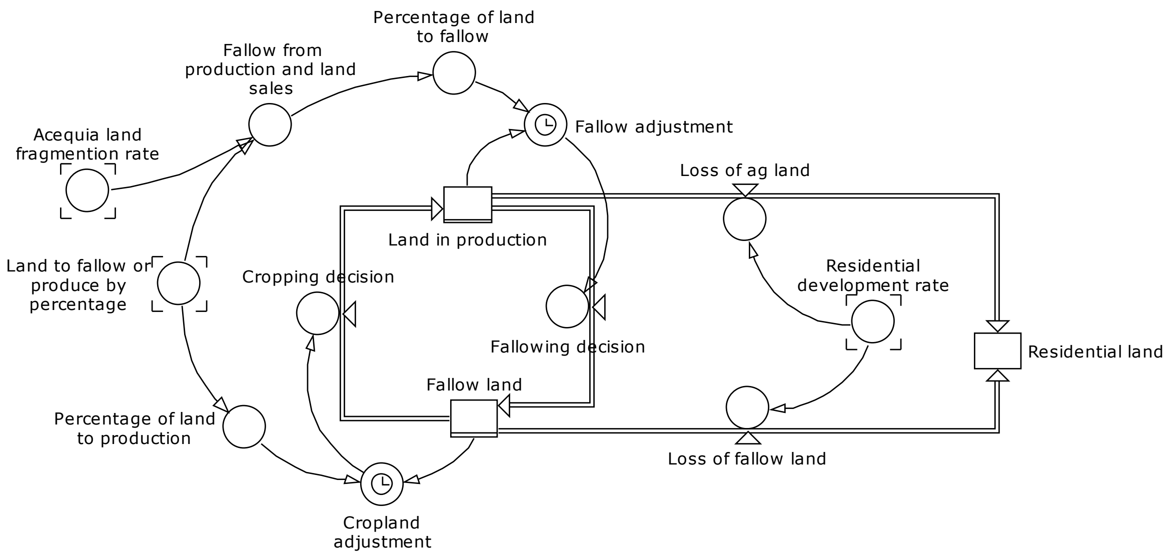

Figure 6. Stock-flow structure of acequia land use.

3.3.2. Parciante time-management

Parciantes are constrained by the amount of time they can work per month and they can work in either their agricultural operation, a job outside the acequia, or some combination of the two. Agricultural production is a priority, but when agricultural profit or loss (a function of crop and livestock profits) combined with external income is not enough to maintain long-term positive financial savings parciantes are forced to allocate more time to external jobs to support themselves (Figure 7). Less time working in the acequia translates into decreased land used for production and more land being fallowed. If economic conditions improve then more time can be spent in agriculture by returning land to production. Residential land is added when the community grows, from either generational transfer among current families or the addition of new community members when current residents sell land to alleviate economic pressures. Parciantes time spent in agriculture is also effected by the number of community neighbors still involved in agriculture and engaged in acequia management (termed acequia mutualism). The greater acequia mutualism the more time parciantes are willing to remain in agriculture (see acequia engagement section 3.3.7. below).

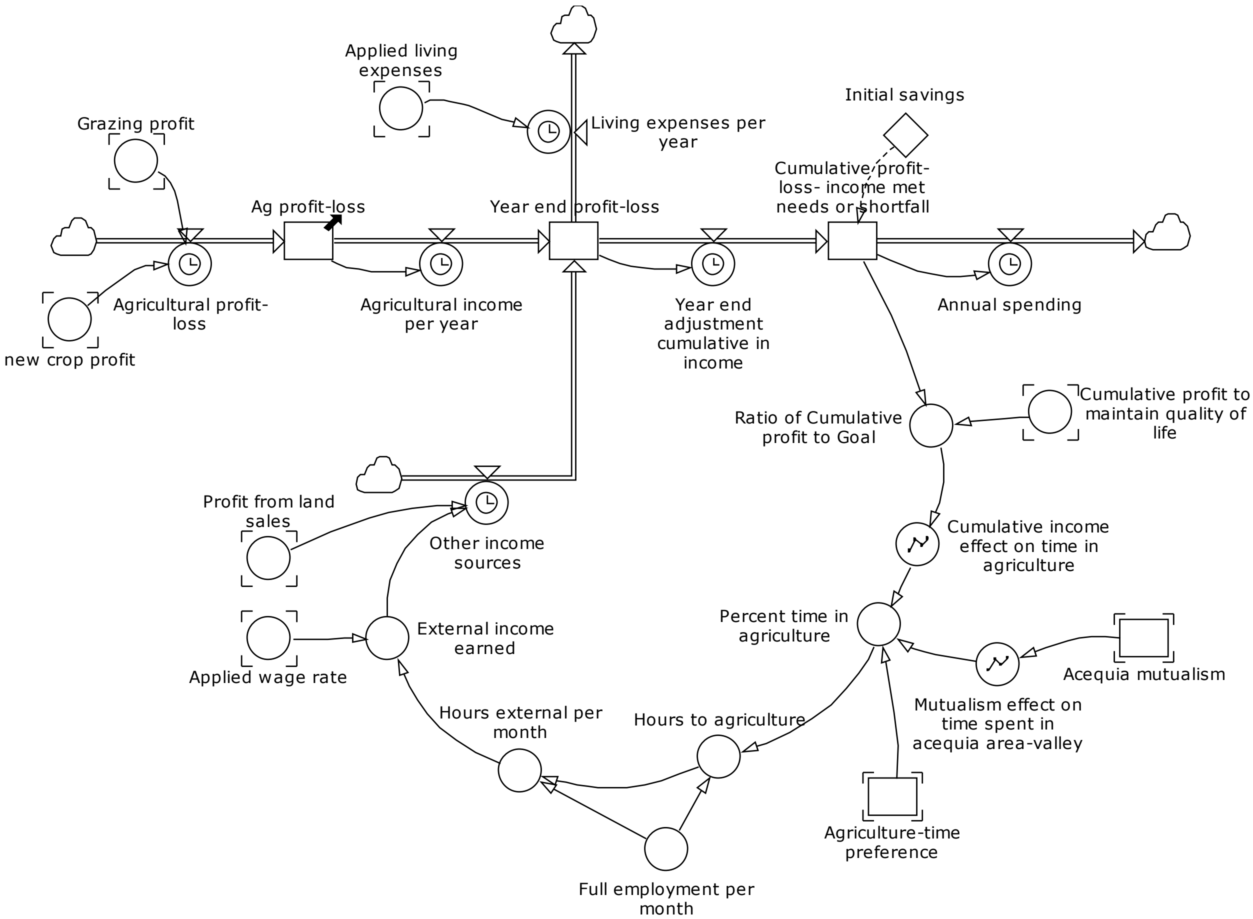

Figure 7. Parciante time management stock-flow structure with associated feedbacks. Each year, agricultural profit and external income are aggregated into Year-end profit-loss. At end of year, this value adjusts the parciate Cumulative profit-loss, which influences Percent time in agriculture for the next year, along with Agriculture-time priority and Acequia mutualism.

3.3.3. Agricultural economics

Agricultural profitability is central to determining how much time parciantes allocate between agricultural and external job activities. Agricultural profitability is driven by commodity output, market prices, and costs of production. Commodity output is the endogenous component which is tied to land in production (Figure 6) and the ratio of land use types within that stock. Land in production is split into four commodity categories: alfalfa, pasture grass, grains and vegetables, and orchards (Figure 8). Prices and costs of production (both expressed as U.S. dollars per unit, usually lbs.) over time are inserted into the model via linkage with an external spreadsheet. These are multiplied by output for each commodity to arrive at gross revenues and costs of goods sold to determine net benefits from agricultural production. We use a net benefits approach to agricultural profitability, which is central to determining time allocations between agriculture and external jobs. The endogenous model components driving net agricultural benefits are the amount of land used for production and time spent in agriculture. Output per unit of land is determined using unique production functions for each commodity with a single independent variable – irrigation water applied (Table 3). These were derived from previous empirical work (Glover et al. 1997; FAO 2012) using evapotranspiration (ET) as the irrigation water input. This links the land and agriculture components with the model's hydrology sector, described below.

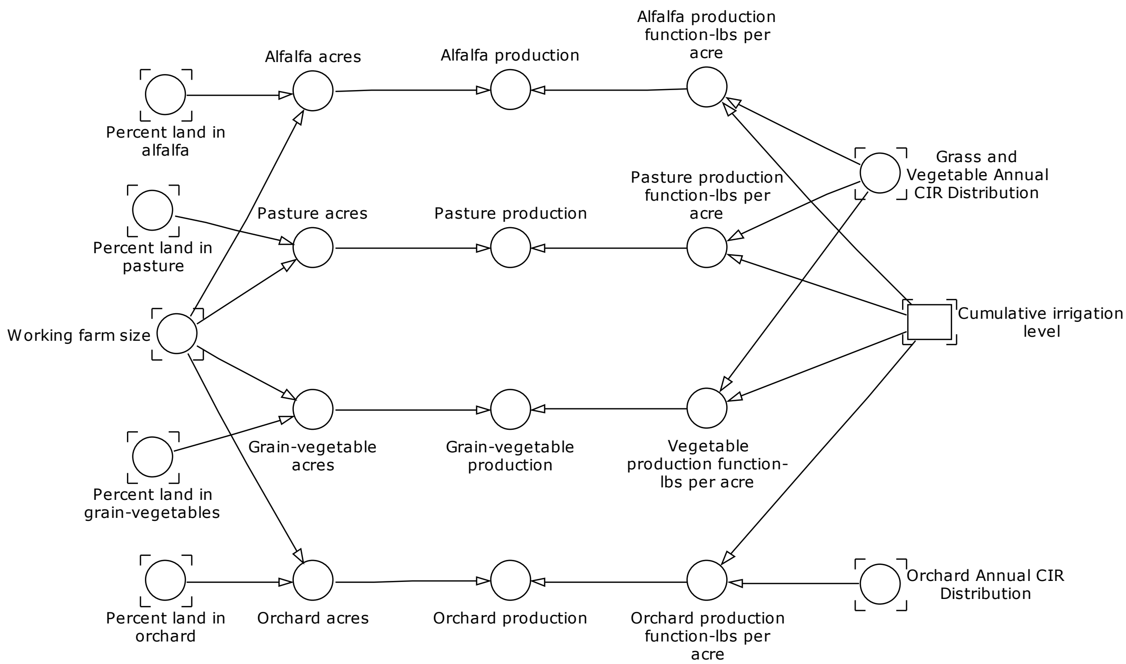

Figure 8. Land use and crop production linkages

Table 3. Crop production functions

Crop	Water Production Function	Units of Measure
Alfalfa	y = 0.15 + 0.13 x ET	y[metric tons/ha] ET[cm]
Pasture Grass	y = -2206 + 289 z	z = water applied [inches] y = dry matter (lbs/acre)
Corn	Y = -7309 + 238.9 x ET	y[kg/ha] ET[cm]
Grains[1]	y = -2323 + 157 x ET	y[metric tons/ha] ET[cm]
Miscellaneous Vegetables[2]	y = -38.9 + 135 x ET	Ungraded yield y (metric tons/ha) ET[cm]
Chile Peppers[3]	y = -7.54 + 0.3327 z	y [ton/ha], z = water applied [cm]
Apple orchard[4]	y = 35.8853 + 0.3905 x ET	ET[cm]

[1] The production function for barley.

[2] The production function for onions.

[3] The average of the production function of green chile (y = -12.1 + 0.5168 * water applied [cm]) and red chile (y = -2.98 + 0.149 * water applied [cm]).

[4] from FAO 2012.

Besides irrigated agriculture within the acequia, parciantes also rely on revenues from cattle grazing in surrounding uplands (Figure 9). The cattle herd size stock includes biological replacement and culling rates since it is assumed that the herd would remain at steady state without any management input. Herd size is constrained by upland grazing area (assumed constant), rainfall variability, and U.S. Forest Service grazing permits, all of which influence forage availability and therefore stocking decisions. These management decisions (restocking and culling) are also influenced by profitability and time spent in agriculture. Since cattle must be fed through the winter months when forage is no longer available (Figures 10) some alfalfa and pasture grass production that is harvested in the summer and fall are stored to feed livestock. If the amount of forage stored does not equal cattle feed demand then the difference is accounted for by purchasing feeds. This links management of the irrigated acequia valleys with upland grazing allotments, both of which are vitally important to sustaining profitability and functional acequia communities.

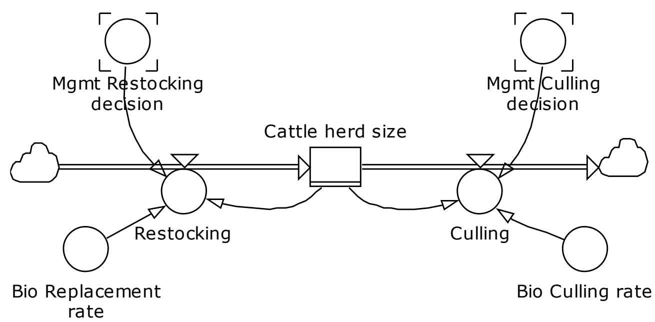

Figure 9. Grazing cattle stock-flow structure.

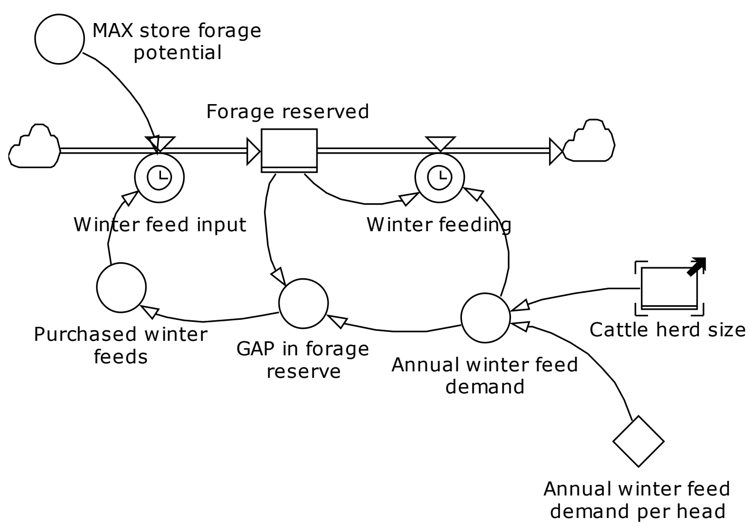

Figure 10. Hay inventory stock-flow structure providing linkages between land use, herd decisions, economics, and time in agriculture.

3.3.4. Acequia hydrology

The hydrology sector begins at the uppermost boundary of the acequia community (i.e., where the acequia ditch diverts water from the main river). Acequia ditch flow is seasonal, with active flow beginning in spring when upland snow melt begins and ending after the irrigation season. Irrigation demand is based on the amount of land in production but limited by river flow volume. Hydrology parameters for ditch and river flow, runoff, ditch and crop seepage, and groundwater inflows were estimated from previous empirical work (Fernald and Guldan 2006; Ochoa et al. 2007; Ochoa et al. 2009; Fernald et al. 2007; Roach 2007). The water input to the crop production function depends on a variety of factors. River flow volume provides a monthly estimate for water available for irrigation (Figure 11). If the stream flow volume is large enough to allow irrigation, then the acequia water diversion rule allows water to flow through the ditch. The ditch flow volume is then partitioned into ditch seepage, crop seepage and runoff, and return flow. Crop seepage and runoff are based on irrigation water applied, which is a function of crop potential ET and consumptive irrigation requirement (CIR). The CIR is defined as the amount of water approved as beneficial use in irrigation. Determined by New Mexico state policy, CIR values vary by crop and month of the year (Table 4). When CIR is lower than ditch flow, the CIR is used as the crop production input, otherwise ditch flow constrains the amount of irrigation applied. Ditch seepage, crop seepage and runoff, and groundwater inflows (assumed constant) are return flow gains, while crop ET and surface water evaporative losses are surface water losses from monthly stream flow (Figure 11).

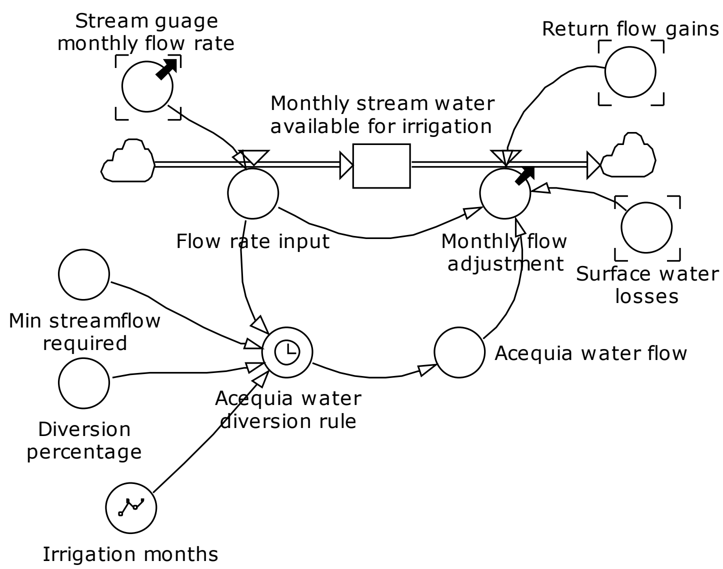

Figure 11. Acequia hydrology stock-flow, with feedbacks for return flow gains and surface water losses.

Table 4. Acequia CIR constraints used in crop production functions. Only months April through September are shown as these are the irrigation season, all other months are 0 cm per month.

Consumptive irrigation requirement (CIR) in cm month^{-1}							
	Apr	May	Jun	Jul	Aug	Sep	SUM
Non-orchard crops	6.1	9.1	15.2	7.6	4.6	3.0	45.7
Orchards	9.1	12.2	18.3	10.7	7.6	3.0	61.0

3.3.5. Riparian habitat

Riparian habitat is important for an array of ecosystem services (e.g., migratory and native bird habitat, erosion protection, carbon sequestration, etc.). In acequia-managed areas, riparian habitat is supported by water inputs from ditch seepage, crop seepage, and crop field runoff. Habitat area was then estimated based on water volume available from those inputs and estimated riparian ET (Figure 12). Since most riparian habitat occurs where land is less intensively managed (e.g., the stream and ditch channel as well as fallow agricultural land), the Fallow land stock acts as a constraint on Riparian habitat. When Riparian to Fallow ratio is equal to 1 (i.e., all fallow land has become habitat), growth can no longer occur. When the ratio is less than 1, riparian growth can continue. This conserves the total amount of land in the model and more accurately describes riparian growth potential.

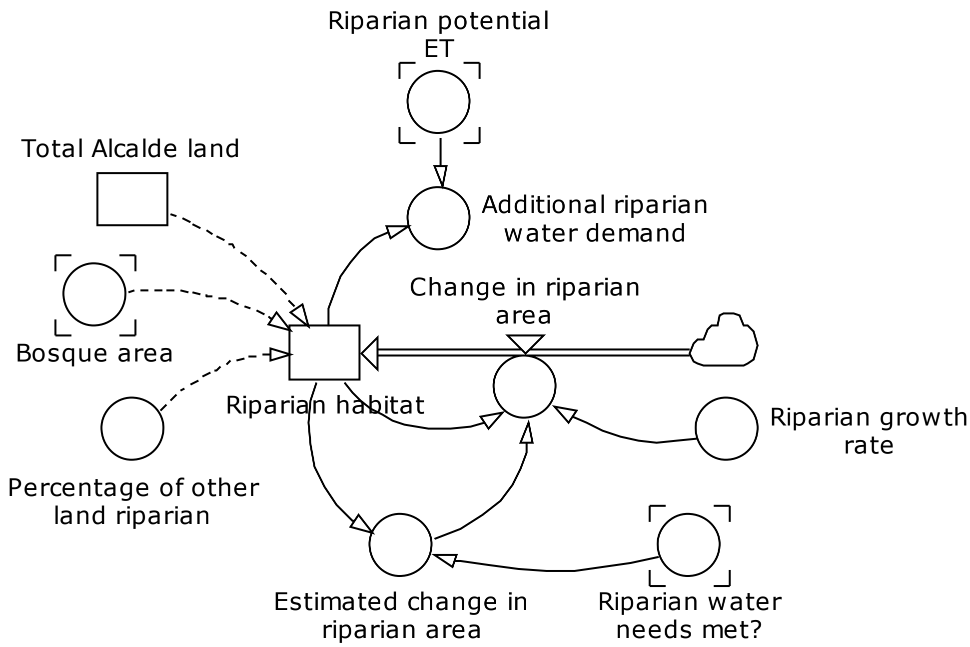

Figure 12. Riparian habitat estimation with stock-flow structure.

3.3.6. Rural community dynamics

The final endogenous component of the model is the community sector. The community sector is comprised of a three stock aging chain: acequia youth, acequia members, and acequia elders (Figure 13). Because some parciantes have to work full- or part-time in an external job (described above), not all community members will participate in acequia management activities. In order to include this an additional stock of absentee acequia members was added to allow youth and current members to flow between active and passive participation in the community. When land is fragmented by parciantes selling property, new community members are introduced that require time to become acclimated to acequia management. This required a fifth stock of new-comers to be added to the aging chain that mimics land sales and fragmentation, community growth, and acclimation of new acequia members.

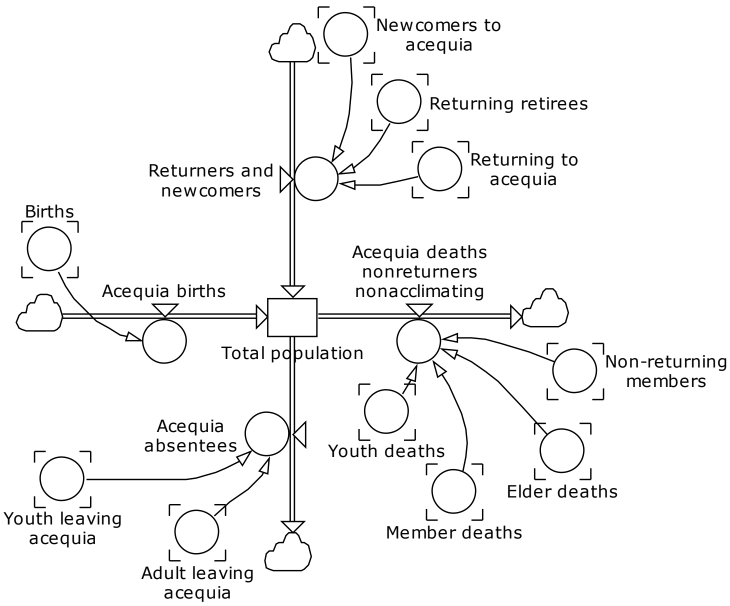

Figure 13. Simplified rural community dynamic, which includes interactions for in- and out-migration of community members and addition of new members through land sales.

3.3.7. Acequia engagement tied to dynamic hypothesis

In order to link the model components together to test the DH, key model variables were used to create an index that controls acequia mutualism (Figure 14). Community mutualism is central to maintaining acequia functions. Using the variables *working farm size*, *percentage of time spent outside acequia*, *percentage of community likely to participate in acequia*, and *fallow land as percentage of total land*, we estimate a Community participation index. Mutualism is built by multiplying the current acequia mutualism level (a value ranging from 0 to 1) by the community participation index and delaying it by the time needed to to take effect (i.e., time needed to build mutualism). If community participation index drops below 2.5 (an arbitrary chosen value), mutualism erodes over time (i.e., time needed to erode mutualism). Acequia mutualism feeds back to the other model components through its impact on parciantes time spent in agriculture function. By doing so, the dynamic hypothesis is more explicitly represented in the model for future hypothesis and scenario testing.

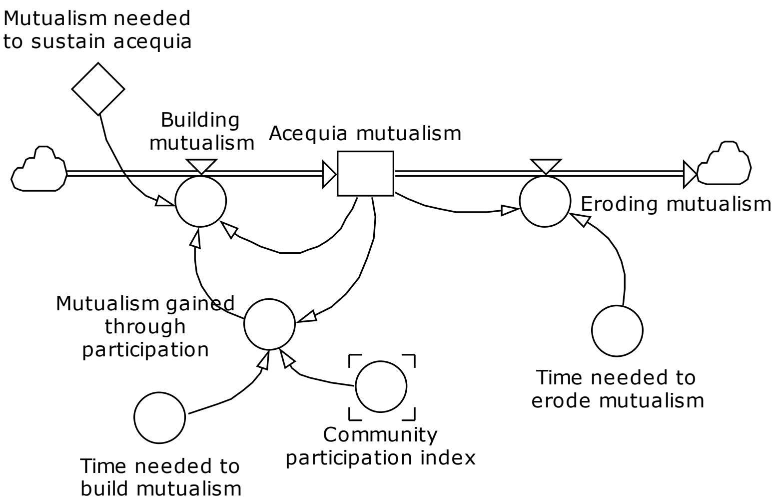

Figure 14. Acequia mutualism structure representing our Dynamic Hypothesis, which ties mutualism and participation in the acequia together with natural resources (land and water).

3.3.8. Exogenous model inputs

Exogenous model inputs include potential evapotranspiration (PET), stream flow levels driven by snowpack in surrounding uplands and mountains, and external economic components of wage rates, commodity prices, and production input costs. The PET rate is calculated each month using long-term average temperature data and incoming solar radiation using the Hargreaves method (Hargreaves 1975; Hargreaves et al. 1985; Hargreaves et al. 2003). Stream flow levels for each calendar month were derived from long-term river flow data available from U.S. Geological Survey data (www.usgs.gov). Agricultural economic inputs (alfalfa, wheat, and cattle prices) were sourced from United State Department of Agriculture (USDA) data available at (http://www.nass.usda.gov/index.asp), while orchard (apple) prices were estimated from Washington Growers Clearinghouse. Wage rates were derived from U.S. Bureau of Economic Analysis (U.S. BEA 2013a and 2013b).

3.4 Model reference modes and calibration

The model's reference modes include stream flows, agricultural profits, community size and demographics, and land use (agricultural and fallow to residential and riparian). Model outputs of each of these variables were compared to historical data. The reference mode time horizon was the time period 1969 through 2008 (social components) and 1969 through 1985 (hydrology components). The major methods we used for judging model adequacy included behavior reproduction tests and Theil inequality statistics (a method of decomposing Mean Square Error, MSE, of predicted values). In general, errors in mean are serious indicators of flawed parameter estimation, errors in variance indicate that the magnitude of variation around the means differ, and errors in covariance indicate that mean and variance discrepancies are small such that dominant trends are described well but point-by-point estimates do not match. We acknowledge that there are more comprehensive tests that should be included in model heuristics. Sterman (2000), Oliva (2003), and Tedeschi (2006) provide systematic approaches to SD model calibration and evaluation. More comprehensive tests are beyond the scope of this model development paper.

4. Results and Discussion

The first community to be calibrated for was Alcalde, NM, using agricultural profits and stream flows as the reference modes. Model predicted agricultural (farm level) profit was compared to Rio Arriba county agricultural profit trends over the period 1969-2008 (Figure 15). Pearson correlation coefficient (r), a measure of goodness for behavior reproduction, was 0.4367 (r^2=0.19). Although a low correlation value shows limited model ability to mimic point-by-point observed data, resulting Theil inequality values showed systemic similarity between observed and predicted values. Ending model bias estimates were 0.006 (mean), 0.024 (variance), and 0.969 (covariance) showed that model average values and variability were near historical levels. Some of the model bias (particularly during the first half of the simulation) is expected since agricultural prices used in the profit function are U.S. national averages (alfalfa, wheat, cattle) and orchard prices derived in a different geographic region (Washington state, U.S., for which data were available over the simulation horizaon). These predicted values can certainly be improved with local price data for all commodities of interest, however data sources for such inputs appear to lacking or sporadic in nature.

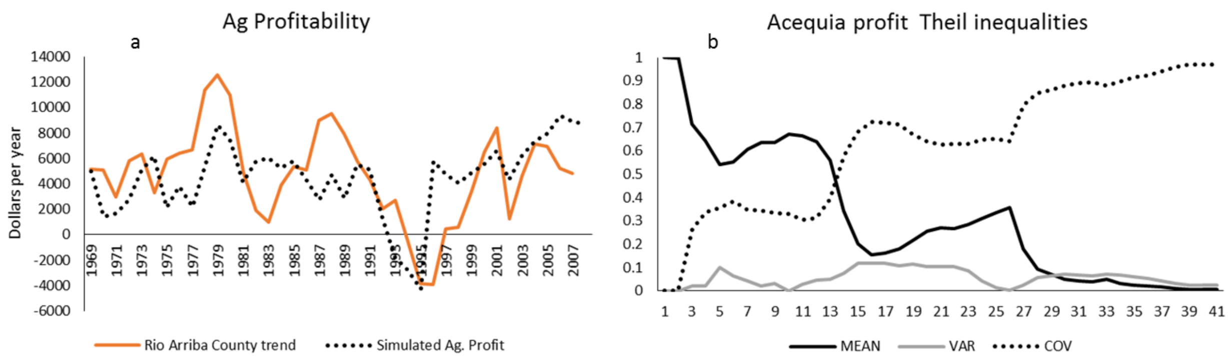

Figure 15. Model reference mode comparison using agricultural profitability plotted over time (plate a) and Theil inequality statistics (plate b).

Model predicted stream outflows showed much stronger calibration values to observed values (Figure 16). The Pearson correlation coefficient between predicted and observed flows was 0.996 (r^2=0.993). Most of the model bias in flows is expressed in the covariance (0.699) and variance (0.259) of predicted values, while mean bias was remarkably low (0.040). Although low errors in mean were encouraging, such a high value in the proportion of error residing in the variance column is somewhat alarming, and may warrant revising or extending the hydrology component of the model (e.g., groundwater-surface water interactions).

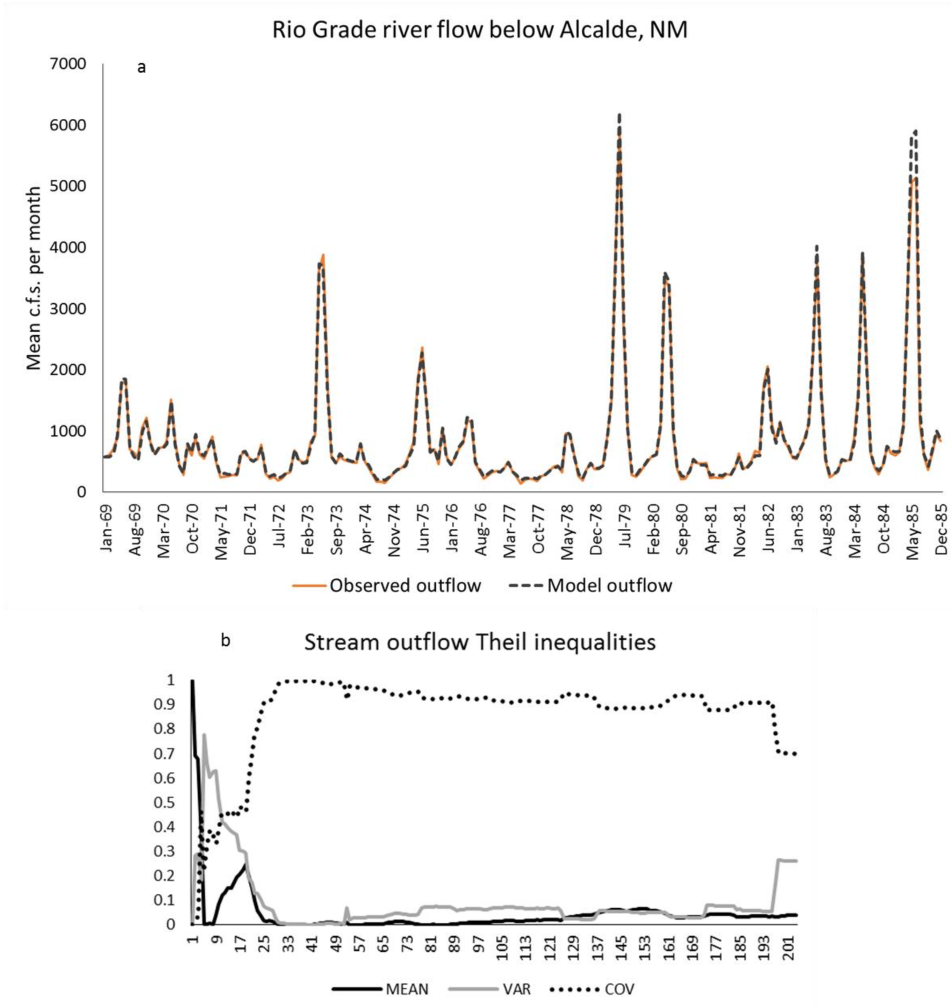

Figure 16. Model reference mode comparison using San Juan Pueblo USGS gauge data (below Alcalde, NM) and model hydrological outflows.

5. Conclusion: Acequia sustainability and resilience

The model presented here is an ongoing work to investigate the sustainability and resiliency of acequia communities in northern New Mexico. While knowledge of the complex interrelations of community, economics, ecology, and hydrology has advanced rapidly in the last 20 years, no model to-date has quantified these connections for scenario testing or robust analyses of potential system behavior in the face of continuous climate, economic, and social changes occurring in the region. We theorize that community sustainability and resilience are rooted in acequia-based connectivity, i.e., the communication and interaction between acequia members and the land and water resources they manage. We posit that traditional acequias create and sustain linkages between natural and human systems that increase community and ecosystem resilience to stressors, such as climate change and economic growth. After initial model development, calibration measures showed strong signs that the model is capable or reproducing observed patterns. Additional data sources are currently being mined or created in order to calibrate the model against land uses and community demographics.

This SD model will be the first model capable of testing for acequia sustainability and resiliency. Future work includes robust sensitivity and scenario testing to identify ‘tipping points’ from which the acequia structure cannot recover. We also aim to integrate this model with previous SD hydrology models in the region that will expand the boundary and number of feedbacks. This will broaden the potential audience and model users from acequia community stakeholders alone to include regional stakeholders and public policy makers.

References

Ackerly, N.W. 1996. A Review of the Historic Significance of and Management Recommendations for Preserving New Mexico’s Acequia Systems. Prepared by Dos Rios Consultants, Inc., P.O. Box 1247, Silver City, NM, 88062 for the Historic Preservation Division, 228 E. Palace Avenue, Santa Fe, NM, 87501.

Brierly, G., Fryirs, K., Vikrant, J. 2006. Landscape connectivity: the geographic basis of geomorphic applications. Area 38.2: 165-174.

Cox, M., Ross, J.M. 2011. Robustness and vulnerability of community irrigation systems: The case of the Taos Valley acequias. Journal of Environmental Economics and Management 61(3): 254-266.

Deaton, M.L., Winebrake, J.J. 2000. Dynamic Modeling of Environmental Systems. Springer Science+Business Media, Inc., New York.

Ewers, M.E. 2005. Combining Hydrology and Economics in a System Dynamics Approach: Modeling Water Resources for the San Juan Basin. Proceedings of the 2005 International Conference of the System Dynamics Society.

Fernald, A.G., Guldan, S.J. 2006. Surface Water-Groundwater Interactions Between Irrigation Ditches, Alluvial Aquifers, and Streams. Reviews in Fisheries Science 14: 79-89.

Fernald, A.G., Baker, T.T., Guldan, S.J. 2007. Hydrologic, Riparian, and Agroecosystem Functions of Traditional Acequia Irrigation Systems. Journal of Sustainable Agriculture 30(2): 147-171.

Fernald, A.G., Yeliz Cevik, S., Ochoa, C.G., Tidwell, V.C., Phillip King, J., Guldan, S.J. 2010. River Hydrograph Retransmission Functions of Irrigated Valley Surface Water-Groundwater Interactions. Journal of Irrigation and Drainage Engineering. December, 823-835.

Fernald, A., Tidwell, V., Rivera, J., Rodriguez, S., Guldan, S., Steele, C., Ochoa, C., Hurd, B., Ortiz, M., Boykin, K., Cibils, A. 2012. Modeling Sustainability of Water, Environment, Livelihood, and Culture in Traditional Irrigation Communities and Their Linked Watersheds. Sustainability 4:2998-3022.

Food and Agriculture Organization of the United Nations. 2012. Crop yield response to water. Irrigation and Drainage Paper 66. ISBN 978-92-5-107274-5.

Ford, A. 2009. Modeling the Environment. Island Press, Washington, DC.

Glover, C. R., C. L. Foster, and R. D. Baker, 1997, *Irrigated Pastures for New Mexico,* Circular 494 New Mexico State Extension Service, at http://cahe.nmsu.edu/pubs/_circulars/circ494.pdf (last accessed 11/29/06).

Grant, W.E., Pedersen, E.K., Marin, S.L. 1997. Ecology & Natural Resource Management: Systems Analysis and Simulation. John Wiley & Sons, New York.

Guldan, S.J., Fernald, A.G., Ochoa, C.G., Tidwell, V.C. 2013. Collaborative Community Hydrology Research in Northern New Mexico. Universities Council of Water Resources Journal of Contemporary Water Research and Education 152:49-54.

Hargreaves, G. H., 1975, Moisture availability and crop production, Trans. ASAE 18(5): 980-984.

Hargreaves, G. H., and R. G. Allen, 2003, History and evaluation of Hargreaves evapotranspiration equation, Journal of Irrigation and Drainage Engineering-ASCE 129.1: 53-63.

Hargreaves, G. L., G. H. Hargreaves, and J. P. Riley, 1985, Irrigation Water Requirements for Senegal River Basin, Journal of Irrigation and Drainage Engineering-ASCE 111(3): 265 275.

Jackson, R.B., Carpenter, S.R., Dahm, C.N., McKnight, D.M., Naiman, R.J., Postel, S.L., Running, S.W. 2001. Water in a changing world. Ecological Applications 11(4):1027-1045.

Khan, S., Yufeng, L., Ahmad, A. 2009. Analysing complex behaviour of hydrological systems through a system dynamics approach. Environmental Modelling & Software 24(12): 1363-1372.

Lane, D.C. 1999. Social theory and system dynamics practice. European Journal of Operational Research 113(3):501-527.

Leung, L.R. 2005. Effects of climate variability and change on mountain water resources in the western U.S. *In* Global Change and Mountain Regions: A State of Knowledge Overview. Pp. 355-366. Huber, Bugmann, and Reasoner (eds.), Springer, Dordrecht.

Mayagoitia, L., Hurd, B., Rivera, J., Guldan, S. 2012. Rural Community Perspectives on Preparedness and Adaptation to Climate-Change and Demographic Pressure. Journal of Contemporary Water Research and Education 147: 49-62.

Nandalal, K.D., Simonovic, S.P. 2003. Resolving conflicts in water sharing: a systemic approach. Water Resources Research 39(12):1362.

Ochoa, C.G., Fernald, A.G., Guldan, S.J., Shukla, M.K. 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(1): 73-81.

Ochoa, C.G., Fernald, A.G., Guldan, S.J., Shukla, M.J. 2009. Water Movement through a Shallow Vadose Zone: A Field Irrigation Experiment. Vadose Zone Journal 8: 414-425.

Oliva, R. 1995. A Vensim module to calculate summary statistics for historical fit. D-4584, System Dynamics Group, Massachusetts Institute of Technology, Cambridge, MA.

Oliva, R. 2003. Model calibration as a testing strategy for system dynamics models. European Journal of Operational Research 151:552-568.

Ortiz, M.A.; Brown, C.; Fernald, A.; Baker, T.; Creel, B.; Guldan, S. 2007. Land use change impacts on acequia water resources in northern New Mexico. J. Contemp. Water Res. Edu. 137, 47–54.

Powersim, 2006, Powersim Software – The Business Simulation Company. http://www.powersim.com/.

Roach, J.D. 2007. Integrated surface water groundwater modeling in the upper Rio Grande in support of scenario analysis. Doctoral dissertation, University of Arizona. Available at http://arizona.openrepository.com/arizona/bitstream/10150/194466/1/azu_etd_2030_sip1_m.pdf (last accessed January 13, 2015)

Rivera, J.A. 1998. Acequia Culture: Water, Land, and Community in the Southwest. University of New Mexico Press, Albuquerque, NM.

Rodrigeuz, S. 2006. Acequia: Water sharing, scarcity, and place. School for Advanced Research Press, Santa Fe, NM.

Shanshan, D., Lanhai, L., Honggang, X. 2010. The system dynamics study of regional development of Manas Basin under the constraints of water resources. Proceedings of the 2010 International Conference of the System Dynamics Society.

Stave, K.A. 2002. Using system dynamics to improve public participation in environmental decisions. System Dynamics Review. 18(2):139-167.

Stave, K.A. 2003. A system dynamics model to facilitate public understanding of water management options in Las Vega, Nevada. Journal of Environmental Management 67: 303-313.

Sterman, J.D., 1984. Appropriate summary statistics for evaluating the historical fit of system dynamics models. Dynamica 10 (Winter), 51–66.

Sterman, J.D. 2000. *Business Dynamics: Systems thinking and modeling for a complex world*. McGraw-Hill.

Tedeschi, L.O. 2006. Assessment of the adequacy of mathematical models. Agricultural Systems 89:225-247.

Tidwell, V.C., Passell, H.D., Conrad, S.H., Thomas, R.P. 2004. System dynamics modeling for community-based water planning: Application to the Middle Rio Grande. Aquatic Science 66: 357-372.

Tidwell, V.C., and C. van den Brink. 2008. Cooperative Modeling: Linking Science, Communication, and Ground Water Planning. Ground Water 46(2):174-182.

US Bureau of Economic Analysis: Regional Economic Accounts, Tables CA25 and CA25N, Total Employment by Major SIC (NAICS) Industry (accessed 18 Oct. 2013), 2013a. http://bea.gov/regional/downloadzip.cfm

US Bureau of Economic Analysis: Regional Economic Accounts, Table CA45, Farm Income and Expenses (accessed 18 Oct. 2013), 2013b. http://bea.gov/regional/downloadzip.cfm

Van den Belt, M.J. 2004. Mediated modeling – a system dynamics approach to environmental consensus building. Island, Washington, DC.

Weinberg, G.M. 1975. An Introduction to General Systems Thinking. Wiley-Interscience, New York.

Winz, I., Brierly, G., Trowsdale, S. 2009. The Use of System Dynamics Simulation in Water Resources Management. Water Resources Management 23:1301-1323.