# APPLYING A SOCIAL-ECOLOGICAL SYSTEM FRAMEWORK TO THE STUDY OF THE TAOS VALLEY IRRIGATION SYSTEM

by

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**Abstract**: This paper applies the social-ecological system (SES) framework (McGinnis and Ostrom, this issue) to the analysis of a SES in the Southwest United States. This SES is composed of 51 interdependent irrigation communities known as acequias. The acequias are descended from Spanish colonists who settled much of what is now New Mexico and Southern Colorado several hundred years ago. In this paper I use the SES framework to explore the combination of social and biophysical features that have enabled the acequias to persist as subsistence-based irrigation systems in a high desert environment since their initial period of settlement.

## 1. Introduction

The study of social-ecological systems (SESs) requires overcoming several challenging problems. While scholars are trained in their own disciplines and perhaps one or two related disciplines, to explain outcomes in SESs requires addressing multiple factors from many disciplines that interact to generate outcomes. Interdisciplinary empirical efforts are thus needed to make progress in the field of social-ecological analysis.

This paper contributes to the study of SESs by applying an interdisciplinary SES framework (Ostrom 2007, 2009) to the SES of the Taos valley acequia irrigation communities in New Mexico. The research question addressed here is: what is the configuration of social and ecological attributes that have enabled the Taos valley acequias to persist in a harsh, high-desert environment for several hundred years? Following this application, I will discuss how we might amend the framework in light of this study.

## 2. The Acequias of the Taos valley in New Mexico

The SES analyzed in this study is an irrigation system composed of 51 acequias in the Taos valley of northern New Mexico, a state in the generally arid Southwestern United States. An acequia is a community of irrigating farmers. The acequia farmers in New Mexico and in parts of southern Colorado are the descendants of the Spanish colonists who moved north along the Rio Grande from Mexico beginning around 1600. They brought with them several traditional Spanish irrigation traditions, most importantly the institutional regime of common property (Rivera 1998). Water within each acequia is considered common property, and compliance with community obligations is required in order for an individual to maintain his/her individual water rights

Each acequia has a well-defined government, led by a mayordomo and three commissioners. The mayordomo decides how water is distributed within his or her acequia and monitors for infractions. The commissioners serve several administrative, legislative, and judicial roles. They are frequently called on to arbitrate disputes and support the mayordomo in enforcing ditch rules.

The majority of the traditionally functioning acequias in New Mexico are in its northern half, which is more mountainous and therefore receives more water. Taos valley is in Taos County, one of the northern-most counties in New Mexico (see Figure 1). The valley is 2,070 meters above sea level and encompasses approximately 400 square kilometers. The acequia-irrigated area in the valley is approximately 40 square kilometers. The valley is bordered to the east and southeast by the Sangre de Cristo Mountain range, which supplies most of the available water through snowmelt. Annual precipitation in the valley itself averages around 30cm per year. The snowmelt water flows westward across the valley until it evaporates, percolates into the ground, or flows into the Rio Grande gorge.

The acequias in Taos valley, like acequias around the state, have sustained themselves as self-sufficient irrigation systems for hundreds of years by adapting to high desert conditions and inevitable periods of drought. They are now facing the threats of economic development, changing demographics, and the penetration of water markets. This study focuses on their social and biophysical properties that have enabled them to historically persist in the face of droughts and general environmental scarcity, leaving the question of their robustness, or vulnerability, to modern disturbances for a subsequent paper.

## 3. Theoretical background

### 3.1. Collective-action problems

This study is based on previous work on community-based management of common-pool resources (CPRs). In order to understand how certain properties might help a community of users manage a CPR, we have to understand the problems such communities face. To sustain themselves over time, the acequias must resolve collective-action problems inherent in managing CPRs. A collective-action problem is a dilemma for a user community caused by a divergence between individual and community-level interests.

A CPR has two characteristics that produce collective-action problems: subtractability and high cost of exclusion. Subtractability means that one user's consumption of a resource subtracts from what is available to others. High costs of exclusion mean that it is difficult to prevent non-users from consuming the resource or to otherwise impose obligations on those who use it.

These properties lead to two primary types of collective-action problems (Ostrom et al. 1994). Appropriation problems result from the challenge of motivating individuals to forego excessive consumption of a subtractable resource, in this case water, where an individual benefits from personal consumption at the expense of the community and the condition of the resource. This is reflected in the commonly observed upstream-downstream relationship between irrigators that pervades irrigation systems. A provision problem, or public good problem, results from the challenge of motivating individuals to contribute to the physical and social infrastructure that makes appropriation possible. This occurs because it is difficult to exclude non-contributors from benefiting from, or free-riding on, the efforts of contributors. In an irrigation system provision includes the construction and maintenance of the irrigation infrastructure.

### 3.2. Models of human behavior

Resolving collective-action problems requires cooperation. Our interpretation of the roles that different variables play in resolving these problems will depend on how we model human actors. I adopt a theory of actors that is supported by existing literature (Jones 2001; Ostrom 2005; Poteete et al. 2010) and includes the following properties: (1) actors are boundedly rational, with limitations on their ability to perceive, process, and recall information; (2) actors are self-interested, valuing personal costs and benefits over social costs and benefits, while maintaining some preferences for equity and reciprocity. This model of the individual means that, while collective-action problems are a challenge for communities, participants do have certain pro-social tendencies that can enable cooperation under certain conditions.

For each individual these conditions include the cooperation of others. In a collective-action situation, the benefits achieved by an individual for his or her cooperation is a positive function of how much other actors cooperate. While the ultimate benefit obtained in an irrigation system is access to sufficient water, this only occurs if other actors cooperate in resolving appropriation and collective-action problems. One irrigator could cooperate by tempering his or her water appropriation or clearing a section of an irrigation canal, and fail to receive any benefits if others fail to do the same.

Thus, an actor's expected benefits rise if he or she can be assured that others will reciprocate his or her cooperation. In these situations we can expect many actors to behave as conditional cooperators, reciprocating the behavior of others. If the benefits expected by an actor are high enough, we can predict that he or she will cooperate, which in turn raises the expected benefits of other actors, who will reciprocate to create a self-reinforcing cycle of cooperation. Self-reinforcing cycles of non-cooperation are likewise possible.

Resolving these issues would be trivial if they did not impose costs. However, making initial agreements and then monitoring and enforcing rules to limit rule-breaking incurs transaction costs. If these are too high, they can overwhelm the benefits of collective-action. Thus, the dilemma for participants is to adopt a set of social features that fit with a particular biophysical environment to provide the benefits needed to maintain a degree of cooperation, while economizing on the limits imposed by bounded rationality and avoiding excessive transaction costs.

### 3.3. Common-pool resource management

Much previous empirical work has been done analyzing how communities can resolve collective-action problems (Agrawal 2003). This has developed a body of theory that forms much of the basis for my interpretation of the acequia case. Here I will briefly discuss the findings and theory that are most directly relevant to this study. First, Ostrom's (1990) design principles constitute a well-established set of conditions associated with sustainable community-based management, and these have been found to be well-supported (Cox et al. 2010). Ostrom's eighth principle, which is particularly important for this study, stresses the importance of multiple levels of governance in managing complex resource systems. The presence of multiple levels of organization has been thoroughly established in many long-lasting community-based irrigation systems (Coward 1977, 1979; Geertz 1959; Siy 1982). Other conditions of Ostrom that are particularly relevant to this study include the presence of: (a) proportionality between costs and benefits experienced by actors; (b) accountable monitoring; (c) graduated sanctions; and (d) conflict resolution mechanisms.

Attributes of the user groups managing a CPR have also been found to be important. Mancur Olson (1965) first theorized that heterogeneity among group members may lead to the presence of a "privileged group" within a community that will disproportionately benefit from and therefore contribute to public goods—such as monitoring, sanctioning, and conflict resolution—that help to sustain collective action.

Heterogeneity in communities can occur along different dimensions—such as cultural or economic—with different implications for collective-action (Baland and Platteau 1996). One such dimension arranges actors along different levels of management authority with respect to a resource system. Such heterogeneity of property rights can create the presence of leadership positions with substantial rights to manage and distribute the resource. Coward (1977) argues that accountable leadership is a standard theme for long-lasting, indigenous irrigation systems. Wade (1988) comes to a similar conclusion, and Siy (1982) discusses the consistent presence of a set of officials that runs each long-lasting *zanjera* community irrigation system in the Philippines, a set that includes a president, secretary, and treasurer. These are precisely the three commissioners that compose each acequia's commission. Finally, scholars have found that, all else equal, small-to medium-sized groups are generally better at sustainably managing CPRs, having fewer transaction costs and more effective reputation-building mechanisms (Wade 1988; Ostrom et al. 1994).

## 4. Methodological background

The SES framework used here consists of four primary components: (1) a resource system, (2) resource units, (3) a governance system, and (4) actors. These are in turn embedded in external social, economic, and political settings, and related ecosystems. The framework then lists properties of each of these components that interact to affect important outcomes (see Figures 2 and 3). These properties form the primary variables in this analysis. More specific versions of these variables are also possible (see Meinzen-Dick 2007 and Brock and Carpenter 2007).

In this case study the interactions of these variables are explored with a kind of within-case process-tracing, which "attempts to identify the intervening causal processes—the causal chain and causal mechanism—between an independent variable (or variables) and the outcome of the dependent variable" (George and Bennett 2005, 206). Ideally this method is more than simply a description of a sequence of events or causal relations. Instead, it can be "an analytical causal explanation couched in explicit theoretical forms" (*Ibid*., 211).

In this analysis these variables interact and produce outcomes through action situations. These are an integral part of the IAD framework upon which the SES framework is based, and were also implicitly included in the SES framework. An action situation occurs "whenever two or more individuals are faced with a set of potential actions that jointly produce outcomes" (*Ibid*, 32). Two examples of such situations include the appropriation and provision activities that individuals take with respect to the two kind of collective-action problems previously discussed.

Action situations seldom occur in isolation. For example, the provision activities in an irrigation system largely determine how much water is available for appropriation. As a result, using the process-tracing method to understand the interactions among a set of variables in the SES framework is aided by the construct of a network of action situations (McGinnis *in press*). This builds on work done by Ostrom (2005, 56).

One important way in which action situations can be linked is across operational, collective-choice, and constitutional institutional levels. Operational rules govern day-to-day activities of a set of participants; collective-choice rules govern the design and alteration of operational rules, and constitutional rules do the same for collective-choice rules. For example, one action situation that is affected by operational rules may in turn be affected by another where these operational rules are determined in a collective-choice arena.

## 5. Data collection and measurement

Several sources of data used in this study were produced as a part of a state-run water adjudication suit in the study area (State of New Mexico ex rel. State Engineer v. Abeyta and State of New Mexico ex rel. State Engineer v. Arellano). In the early 1990s, 36 senior acequia officers were called upon to testify regarding their traditional water management practices in the valley. This was done so that the court's decision on water allocation and distribution in Taos would reflect these traditions and customs. These testimonies were obtained and used as a basis for evaluating the acequias' water management institutions. These data was validated with original on-site data collected through in-person interviews. A total of 13 interviews were conducted with acequia mayordomos and 30 interviews were conducted with acequia commissioners.

Additionally, the New Mexico Office of the State Engineer (OSE) produced a series of hydrographic survey maps between 1969 and 1971 as a part of the adjudication process, which was initiated in 1968. These maps depict the canals and irrigated land for each acequia in Taos valley. Two other public sources of data used for this study were a series of satellite images from NASA's Landsat program and time series data from several stream gages in the valley placed there by the United States Geological Survey. Finally, previous work on the acequias in Taos valley was used to validate other data (Baxter 1990, 1997; Rivera 1998; Rodriguez 2007).

The unit of this analysis is the SES comprised of 51 acequias, and the variables were measured at this level. This analysis is closely related to another, the unit of analysis of which was the 51 acequias (Cox and Ross 2011). Some of the variables measured at the SES scale were inferred from measurements of variables at the acequia-scale. The statistical relationships explored in that study also support some of the causal inferences made in this paper.

All of the variables are ordinal or categorical. The ordinal variables each had three potential values. These took on the values of "strong", "moderate", and "weak" or "high", "moderate", and "low," depending on what language made the most sense for each variable. Several of the categorical variables are binary, usually indicating whether or not a particular feature is present or not. The variables themselves are presented using the structure and notation from the original framework. The first tier is represented in uppercase letters and the second with a number (see figure 2). When used to create a more specific variable, the third tier is labeled with a lower-case letter. For the resource system, of which I create subcomponents, I add a letter to the first tier (e.g., RSG for the groundwater system) to indicate which subsystem variable is being discussed.

## 6. Historical structure of the acequias as a SES

In most social-science-oriented statistical research, the relevant variables are first determined and their values are measured. Then, their statistical importance is examined, usually by running a model. Similarly, in this paper I will first present the structure of the SES through the values of its relevant variables, and then describe how this structure has functioned to produce the acequias' robustness over time.

However, instead of describing a set of variables in isolation from each other, I will describe how the relevant variables work together to produce a structure. This reflects the fact that the variables do not in fact work in isolation, and that as the data were collected and interpreted, certain variables from the SES framework were shown to be relevant because of how they apparently interacted with others to produce outcomes. Their relevance, measurement, and causal importance were all determined simultaneously.

As such, in this section I will not begin with a list of the relevant variables and a discussion of their values in this case. Instead, I will present each of these through a discussion of the larger social-ecological structure of the acequias. These variables and their interpreted values are presented in table 1. I will begin by describing the biophysical context. Then we will discuss the governance system that is layered onto the natural and built environment of the acequia SES.

### 6.1. The biophysical context

The environment that the ancestors of the current Taos acequias colonized is harsh: a desert at 2,070 meters above sea level. It is in these types of conditions that common property arrangements often arise, when environmental scarcity requires cooperation in order for individuals to obtain the resources they require to subsist. In this case, like many others, the motivation for common property and the collective action it requires has been further strengthened by the historic economic poverty **(A2a)** of the irrigators and their extremely high historical dependence on the resource system **(A8)** as the only means of obtaining food. In such environments, individual must cooperate if they are to survive.

While the initial SES framework implied that a SES only would have one of each of the first-tier components, here I expand this to describe several resource systems used by the acequias. These are: (1) an irrigation infrastructure system; (2) a set of groundwater aquifers; and (3) a land system, which largely lies between the irrigation and groundwater systems, and is used to grow crops and as pasture for livestock.

The primary resource unit is water, while on the land system the acequias also had livestock graze on pasture areas. In this analysis I shall focus primarily on the water unit and not livestock. The livestock unit and the historic pasture lands that many acequia members used are historically important. However, it does not seem that these were managed as part of the traditional acequia water and irrigation governance regime, and much less information is available about how such lands were managed. Thus, for this analysis these will largely remain exogenous as a factor I recognize as helping the acequias persist and resolve the collective-action problem associated with water management.

Each resource system has one of the two defining principles of a CPR: high cost of exclusion **(RS9)**, while the other defining property belongs to the water resource unit, which is moderately subtractable **(RU8)**, meaning that once a farmer turns a quantity of water into his or her fields, it is unlikely that this same quantity of water will be available to other farmers.

While the water resource unit is moderately renewable **(RU2)**, periods of scarcity are common. It is also highly mobile **(RU1)**, and is highly heterogeneous in its spatial **(RU7a)** and temporal

**(RU7b)** distribution. Spatial heterogeneity means that there is extensive variability in water availability across the valley. Regarding the temporal distribution of water, USGS (2010) stream gage data show that the amount of water that is available through surface runoff is highly variable intra- and inter-annually. This is the source of the vast majority of water for the acequias, as precipitation levels in the valley only average around 30cm per year, an amount insufficient for agriculture. Figure 4 shows the annual flow of the two largest rivers in the valley in cfs. In addition to showing generally low levels of streamflow, these data show that drought years occur frequently. Here we define a drought year as one in which annual streamflow in CFS is at least one standard deviation below the historical mean. On the Rio Hondo, 12 drought years occurred since 1965, while 14 have occurred in the Rio Pueblo de Taos. During these periods, appropriation problems can be severe.

There are several biophysical features of the acequias which moderate this scarcity. To begin, hydrological work by Barroll and Burke (2006) and Drakos et al. (2004) indicates that the relationship between surface water and groundwater in Taos valley is quite strong, and that withdrawals from one affect the availability of water from the other. I ascribe this property of water permeability to the land resource system **(RSL10)**. In hydrological analyses of acequias systems in other parts of New Mexico, Fernald et al. 2007 and Fernald and Guldan (2006) have found that acequia irrigation raises nearby water tables in an area they label the "irrigation corridor." This is in part a result of the low level of technology **(A9)** employed by the acequias—mostly shovels and sticks—to maintain irrigation canals that are earthen or unlined **(RSI4a)**. Because they are unlined, these ditches allow water to percolate through the ground and into the shallow groundwater aquifers.

In part due to the tight connection between the surface and the groundwater in Taos valley and the acequias' unlined canals, the shallow aquifers in the valley store water after it has percolated down following streamflow and irrigation events **(RSG8)**. This water frequently seeps back up to the surface for downstream farmers to use. Cox and Ross (2011) found that acequias with more irrigated land in the "irrigation corridor," where higher water tables are more likely to make groundwater available, perform better over time. In fact, interviewees frequently reported the availability of water through seepage when the main stream or canal was dry during a drought. This replicates findings reached by Rodriguez (2007, 47) in her own anthropological study of the Taos acequias.

This storage capacity is particularly important due to the high variability and low predictability **(RSI7)** and low storage capacity **(RSI8)** of surface water that the Taos acequias must contend with. A second way that the acequias moderate the subtractability and scarcity of the resource unit and augment downstream availability is through the use of *desagues*, or drainage channels **(RS4Ib)**. These drainage channels return unused flows back to the main river downstream of an acequia, ameliorating upstream-downstream conflicts over water.

Finally, the acequias have historically ameliorated water scarcity by using a pasture system to augment the nutrients and energy that their agricultural crops provide them. Much of this pasture was historically on commonly held high elevation lands outside of individually owned tracts. In an arid environment, pasture can be the most productive use of large amounts of land, as mobile livestock can graze on a large enough expanse to effectively make use of an amount of rainfall that otherwise would be too disbursed to allow for subsistence activities.

### 6.2. Governance network structure: GS3

There are other important features of the resource system, but these are best understood in the context of the social and institutional features of the SES. We now turn to these features, beginning with a picture of the acequias' governance system. Figure 5 shows the network of action situations that the acequias have constructed in order to address the collective-action problems that they face. Each box represents a type of action situation. First I will discuss the governance structure of the acequias that produces this network. Then we focus on individual action situations.

We can understand the network of action situations by viewing the interactions between individual acequia farmers as a social network. There is a well-established research program studying social networks, and a more recent branch of it that uses network analysis to better understand natural resource management (Bodin et al. 2006; Bodin and Norberg 2005). A network is a collection of nodes and the links that connect them. In this discussion the nodes are individual farmers. Defining a single type of link between the acequia farmers and measuring it at a particular point in time in Taos valley proved to be both misleading and impractically difficult for this study. There are multiple ways in which the farmers in the valley interact, and it is the combination of these different types of interactions that forms their social structure. Crumley (1995, 3) introduced the term *heterarchy*, or "the relation of elements to one another when they are unranked or when they possess the potential for being ranked in a number of different ways," to describe how community members can relate to each other in multiple ways.

The acequia farmers in the valley interact in a heterarchy of relationships, the combination of which produces an intelligible community structure, but the understanding of which is not necessarily aided by formal network analysis via the computation of statistical network properties. Nevertheless, based on available data, important qualitative descriptions of this heterarchy can be usefully presented. This analysis focuses on four types of networks within the heterarchy: water distribution, monitoring, conflict resolution, and provision.

**The water distribution network:**

The primary actor within an acequia with respect to water distribution is the mayordomo. It is universal in the acequias that the mayordomo is in charge of this process and has a connection to every member in an acequia in this network. Farmers either call the mayordomo when they want water or attend regular meetings where they receive their allotted time to irrigate. In both cases the mayordomo maintains a list of who has the right to irrigate and when they can. It is a rotational based distribution system **(GS5b)**, and users are given water rights in proportion to their land rights, which are distributed heterogeneously **(GS4a).** This relationship occurs only within acequias: mayordomos do not have authority over members of acequias other than their own. Thus, these interactions are limited to the appropriation action situation within each acequia.

Collective-action problems occur between acequias in the same way as they occur between individuals within acequias. These problems are addressed through inter-acequia water sharing agreements, or *repartamientos*, which also represent interactions within this network. Repartimientos are the result of past conflicts, and involve meetings between acequia officials (sometimes mayordomos, sometimes commissioners, sometimes both) in times of resource scarcity. In these meetings, acequia officers meet mostly to affirm historically held agreements as to how water is to be divided up between them in times of scarcity. Not all acequias are involved in water agreements. These meetings occur in the diversion action situations from figure 5, which is the 2nd level equivalent to the 1st level appropriation action situation.

**The monitoring network:**

These monitoring activities belong in the appropriation action situation for each acequia. This network is composed of the interactions between acequia members that involve monitoring for rule-breaking behavior. There are two ways this occurs within the acequias. First, the mayordomo monitors the behavior of each one of the members within his ditch. The effectiveness of his monitoring is enabled by his authority and local knowledge as the central distributor of water.

Secondly, farmers who are geographically proximate to each other tend to indirectly monitor the actions of their neighbors (see another example of this in Trawick 2001). This process is referred to as “walking the ditch,” where a farmer who is not receiving water during his turn will walk upstream along the irrigation ditch to see who is taking it out of turn and preventing it from reaching his or her headgate. These relationships do not occur between a member and every single other member. Rather, the probability of any two members being linked in such a way increases as their irrigated parcels converge.

This decentralized monitoring is enabled by the fact that acequia farmers have traditionally lived on the private parcels of land that they irrigate, which are spatially clustered **(A4a)**. These parcels all cluster near the river or a main canal, and are contiguous within an acequia, while acequias are contiguous to each other. This contiguity, when combined with a rotational water distribution system, facilitates low-cost, decentralized monitoring within each acequia **(GS8a)**. During the rotation, the member whose turn it is to have the water serves as a de facto monitor of all his neighbors. This, in turn, helps enable the sanctioning the acequias employ, which is proportional to the severity of the offense, or graduated **(GS8b)**.

**The conflict resolution network:**

The acequias exhibit a tiered system of enforcement and conflict resolution, where the initial step involves the mayordomo confronting a rule-breaker. In more severe cases, commissioners may become involved as a source of arbitration. These links only occur within each acequia: an acequia’s officials do not have authority over the members of another acequia. These activities occur in the conflict resolution action situation in the first level of figure 5. The conflict resolution at the second level occurs between officers when they meet to discuss their repartimientos. Essentially, these occur when the officers shift from a more standard operational arena to a more collective-choice-oriented arena, where they address whether they will continue to use a particular set of operational rules for distributing the water among their acequias.

**The provision network:**

The provision network is constituted by those interactions that acequia members engage in as they build and maintain the irrigation infrastructure. The earthen canals the acequias use must be periodically cleaned of debris that naturally accrues in them. Most of this activity occurs during an annual event that each acequia has historically held, called *la limpia de la acequia* (the cleaning of the ditch). Obligations to contribute to provision are proportional to the amount of water rights owned **(GS5a)**, which maintains a sense of equity in spite of the uneven distribution of those rights.

This network is somewhat different from the first three, in that it exists almost exclusively with acequias. The mayordomo is again the central figure in these activities, personally directing a group of acequia members as they clean the main ditch that the common property of all of the members of the acequia. Individually owned headgates or smaller branching canals are managed at a lower level, either by smaller subgroups within the acequia, or by the individual owners themselves. These lower-level interactions can be thought of as the provision-based analog to the more decentralized monitoring that takes place between neighbors.

### 6.2.1. Network centrality: GS3a

The acequias' governance networks contain important degrees of centrality. Centrality can be defined as the presence of "some high-ranking nodes in the network that have a significantly higher-than average number of links and/or have links stretching from beyond their local network neighborhoods. Well connected nodes, i.e. hubs, in the network, are most likely of higher importance than others that are not so well connected" (Janssen et al. 2006).

This centrality results from a heterogeneous distribution of authority, or property rights, that the farmers are given with respect to the resource system and units (Schlager and Ostrom 1992, 250-251). Parciantes generally only have rights to access the resource and withdraw water. Mayordomos have access rights as regular members, but also decide how the water is distributed to right holders. Finally, commissioners, together with the mayordomos, monitor who has a right to access the water, and commissioners, being in charge of writing bylaws, have the right to determine how rights may be transferred. This heterogeneity in property rights in turn creates leadership roles for acequia officers **(A5)**.

In their leadership roles, mayordomos dominate the water distribution, monitoring, and provision networks. They direct la limpia de la acequia, are in charge of deciding who and in what order each farmer on their ditch receives their water, and actively monitor that this distribution system is complied with. The importance of mayordomos that result from this high centrality has been highlighted previously (Crawford 1988). Commissioners are also unusually well-connected in the water distribution network, through their involvement in repartamientos. Finally, mayordomos and commissioners are hubs in the conflict resolution network. These relationships involve internal confrontations and arbitration within and between acequias.

### 6.2.2. Network modularity: GS3b

In a modular network, nodes cluster to form natural groups, within which they are more highly connected than they are to nodes within other groups. Each of the acequias in the valley naturally forms a module in a larger network of relationships among the rest of the farmers. Much more intensive and regular interactions within all four networks occur within acequias than without. Less common but important connections exist between many acequias (primarily through their officers) that enable them to resolve collective-action problems on a larger scale through repartamientos.

The modularity of the overall network accomplishes several things. Primarily, it decomposes the larger irrigation system into subgroups, with more frequent interactions within than between subgroups. Each acequia as a subgroup, or module, in this case faces a set of collective action problems imposed by their biophysical relationships. However, each group can resolve these collective action problems independently of other groups. This decreases the number of individuals **(A1)** involved in resolving any particular collective action problem.

It is well-established in CPR theory that smaller groups are better able to resolve collective-action problems due to the decrease in transaction costs involved (Ostrom et al. 1994). As defined earlier, transactions costs are the costs of monitoring and enforcing agreements. While the transaction costs of monitoring and enforcement for the entire system may not be decreased in absolute terms by a modular community structure, in a system that is modular like the acequias' system is, the costs of monitoring and enforcement are divided up amongst each of the modules, each of which can them more easily monitor and enforce its own set of internal agreements.

### 6.2.3. Multiple levels of organization: GS3c

When combined, the properties of centrality and modularity can create a hierarchical network with multiple levels of organization (Barabasi 2002), which is shown in figure 5. The first level occurs within modules, and the second occurs between them, typically via the hubs. The presence of multiple levels of organization has been thoroughly established in community-based irrigation systems (Coward 1977, 1979; Geertz 1959; Siy 1982), and in a general class of systems known as complex adaptive systems (Holland 1995).

A primary advantage of such a hierarchical network in a social system is that it lowers the number of individuals involved in resolving collective-action problems each multiple level. As just discussed, the modularity divides the network up into smaller groups, each of which is able to deal with its own internal collective action problems more easily. The next critical step is at the second level, when the hubs of the network serve as representatives of their individual modules in resolving collective-action problems among modules. In the acequias' case, it is the mayordomos and commissioners as hubs who primarily take part in the repartimientos.

In the Rio Hondo system in the northernmost part of Taos valley, for example, there is first the level of acequia organization, and secondly there is an agreement to divide what is available at the first main headgate to three separate groups of acequias. This is a standing proportional arrangement that is primarily enforced in times of shortage. Within these groups allocation decisions also need to be made (meaning that for these particular acequias, figure 5 would have an additional level between levels 2 and 3). This network structure is both modular and centralized, producing a hierarchical structure.  This organization feature enables the acequias to govern a geographically extensive resource system from the bottom up.

#### 6.2.4. The third level of governance

The networks just described constitute the first two levels of governance shown in figure 5. There a third level as well, constituted by external government. The acequias in New Mexico have been affected by several different government organizations during their history. The governmental regime presiding over what is now New Mexico can be broken down into four periods: (1) the colonial or Spanish era, (2) the Mexican era, (3) the U.S. territorial era, and (4) the U.S. statehood era. Through these periods, the external government, primarily in the form of local courts **(GS1a)** played a crucial role in land settlement and arbitrating disputes **(GS9)** amongst waves of settlers.

In the Spanish era which began in the 1600s, a provincial governor appointed regional *alcaldes*, and the two positions constituted a two-tiered conflict resolution mechanism for settlers and irrigators. In 1821, Mexico won independence from Spain. This led to several changes, including the transition from governance by local alcaldes to governance by *ayuntamientos*. The *ayuntamiento* in Taos worked to resolve "allocation disputes between competing settlements, questions of priority, rights-of-way, acequias maintenance, and related problems" (Baxter 1997, 32). In 1837, ayuntamientos were abolished, and *juezes de paz* (judges of peace) replaced their water management and conflict resolution functions. Following the U.S. Mexican war in 1848, a new territorial government system was put in place including "an executive, a court system, and an elected legislative assembly" (ibid., 65). Within the court system, the local probate court proved to be most critical governmental body for resolving water disputes in ways previously accomplished by alcaldes, ayuntamientos and juezes de paz. Several decisions made by territorial probate courts stand today as formal repartamientos.

### 6.3. The network of action situations

With this network picture in hand, we can better understand figure 5. At the first governance level, which occurs within each acequia,  there are three types of action situations, two devoted to resolving the central collective-action problems described earlier (appropriation and provision), and a conflict resolution situation which is used less frequently. At the second level there is a diversion and a second conflict resolution situation. The diversion situation summarizes all of the interdependent actions taken by the mayordomos to divert water to their particular acequias. It is the second level equivalent to the appropriation situation at the first level of governance. The second conflict resolution situation represents the attempts among acequia officers to discuss and reaffirm their repartimientos, generally during droughts. Because acequias do not normally share extensive irrigation infrastructure, there is not a strong provision problem at this second level. Finally, the third level of governance is constituted by a single collective choice arena that is invoked most infrequently, again to resolve conflict.

The links in this network have different significations. In the first level, the appropriation situation affects the provision situation by providing the water that is the source of the expected benefits that motivate individuals to incur the costs of maintaining irrigation infrastructure. The provision situation in turn affects the appropriation situation by making the collection of these benefits possible through infrastructure maintenance. The conflict resolution situation primarily interacts with the appropriation situation, for it is here that the greatest conflicts arise over water use. It does so as an arena in which conflicts over appropriation can be resolved.

The appropriation situation at the first level takes place in the context of the diversion situation at the second level. It can also affect the diversion situation when appropriation decisions by members of one acequia affect how much water is available downstream for a mayordomo to divert into the main headgate for his or her acequia. In the diversion situation, mayordomos and commissioners determine how much water can actually be appropriated within their acequias. This diversion situation is affected by a collective-choice conflict resolution situation that takes place whenever the same acequia officers potentially reconsider changes to their operational rules (how much water each diverts to their acequia). It is also affected by a third-level collective-choice conflict resolution situation in the form of the local courts, that has taken place much less frequently than the others, but has had tremendously important impacts by solidifying water-sharing agreements that have stood for more than a hundred years.

### 6.4. Property rights regimes and bottom-up resource management

We can complete this account of the acequia SES structure by adding one final layer—that of property right regimes. This layer helps us understand how the governance system shown in figure 5 actually applies to the resource systems that it governs. The acequias employ a mix of property rights regimes to govern the different resource systems—primarily the irrigation resource system and the land system contained with acequia boundaries. These vary with the levels of governance shown in figure 5 and relate to the branching quality of the irrigation infrastructure **(RS4Ic)**. This begins at a main canal off of a river, which then subdivides several times until it ends at a particular farmer's headgate.

Regarding this infrastructure, at the lowest level, individuals privately own the portion of the ditch that immediately feeds their parcel of land. The main canal for each acequia is common property. Between these two levels there may be informal arrangements by a group of members to manage a common sub-canal that feeds each of their headgates. This would also be managed by a common property arrangement.

The property rights regarding the land resource within acequia boundaries are somewhat similar. Individuals own their privately irrigated parcels, while a certain area around the common property irrigation canal is also common property, and each acequia has easement rights within this area. The property rights regimes applied to pasture lands were somewhat distinct and are not thoroughly discussed here. Surface water is also common property and its appropriation is subject to community rules. Groundwater, despite its importance, is not governed by any property rights regime, probably because the physical boundaries around it are so unclear. Thus, physical boundaries on the resource system are clear at for the irrigation system **(RSI2)**, but unclear for the aquifers **(RSG2)**. The boundaries for the land system are relatively clear at the parcel level **(RSL2)**, but may have been substantially weaker for commonly owned pasture lands.

We can now complete the picture begun with figure 5 to understand how the acequias govern the irrigation resource system and parts of the land system from the bottom up. To begin, they have a multilevel governance structure. The governance units at each level correspond to successively larger geographic sections of each resource system. Moreover, the social structure reflects the hierarchical branching quality of the physical irrigation infrastructure (see Coward 1977 for this property in other systems). Small canals feed smaller areas at lower levels, while larger canals feed larger areas at higher governance levels. Finally, with each successive level, there is transition to a distinct property right regime.

This is all summarized in figure 6, which shows the geographic units that correspond to each level of governance. At level 0, individuals own their own plots of land and irrigation turnouts. They do not, however, own the water that is turned onto their fields. This resource unit, along with the main canals the convey it, is common property of each of the acequias, which are positioned in level 1. Then, the area that is encompassed by the repartimiento for all 8 acequias is positioned at level 2. The property regime here is labeled public property, although this does not mean that it is governed by the state. It simply means that the main river and the water in it are effectively considered to be owned by all of the acequias, or at least that no one of them can use it without regard for the rights of the others.

## 7. How the structure produces outcomes: interactions

We have explored the structure of the acequia SES, with some references to how it functions. We will now address this topic directly by exploring how the structure enables the acequias to resolve the primary collective action problems of appropriation and provision. Each of these is modeled with a causal diagram in order to make the method of process tracing described earlier explicit. There are three types of connections between variables in these diagrams: (1) necessity; (2) sufficiency; and (3) subset. A is necessary for B if B cannot occur without the presence of A. A is sufficient for B if A's presence ensures B's presence. The subset relationship is not causal; it indicates that B is a type of A. In the diagrams, necessary relationships are indicated by solid arrows, sufficiency relationships by dotted arrows, and subset relationships by dashed arrows (see figure 7).

Another commonality among the diagrams is the dependent variable. This is the difference (or ratio) of benefits over costs. If this ratio is maintained at a high enough level, the conditional cooperators described earlier will each contribute to resolving the appropriation and provision collective-action problems, which is the final variable shown in each diagram. Because these benefits at the individual level are a function of the collective-action of others, the two variables engage in a self-reinforcing causal loop, which can be maintained as long as the supporting factors do not experience excessive disturbances.

## 7.1. Appropriation action situations

The appropriation situation within the acequias is shown in figure 8, and consists of a set of individual decisions made by members about how much water to divert into their private irrigation ditches and fields. Cooperation means tempering water use so that other users can also share in the benefits of use. To explore this situation we begin with a set of features that increase the expected benefits of cooperation. The acequias have a set of rules that create the position of mayordomos and commissioners and give them certain authorities. This produces a heterogeneous distribution of property rights **(GS4a)** which in turn creates leadership roles for the mayordomos and commissioners **(A5)**, and gives them centralized roles in the governance networks. The officers' property rights enable them to produce several important public goods that help maintain collective-action in the acequias. In this situation these primarily include water distribution, monitoring **(GS8a)**, sanctioning **(GS8b)**, and conflict resolution **(GS9)**.

Each mayordomo also directs a time-based or rotational water distribution method **(GS5b)**. This rotational method of distribution, when combined with the geographic clustering of user locations **(A4a)**, enables a highly effective, low-cost monitoring system within each acequia, where each member in turn serves as a monitor for the ditch during their allotted time to irrigate **(GS8a).**

The features discussed thus far, such as monitoring and public good provision, generally incur some moderate transaction costs in order to increase the net benefits expected of cooperation. These transaction costs are in turn moderated by several other features, beginning with the modularity of the governance structure **(GS3b)**, where each acequia has more frequent and regular interactions between its members and officers than with other acequias. This property increases the number of collective-action problems that must be resolved for the SES as a whole, but decreases the number of participants **(A1)** involved in any one of those collective-action problems. This social modularity mirrors the branching structure of the resource **(RS4Ic)**, where modules manage sub-branches of the larger irrigation system.

One feature that increases expected benefits without incurring transaction costs is the proportionality between costs and benefits, where the amount water rights allotted to each member is proportional to the amount of labor and/or resources they are expected to contribute **(GS5a)**. This proportionality produces a sense of equality within the acequias, despite their heterogeneous distribution of property rights. While not increasing an extrinsic benefit, this does increase benefits for individuals with internalized norms of equity (Ostrom 2005, 146). A final social feature which is important is a high level of resource dependence **(A8)**. This aids cooperation by dramatically increasing the costs of not cooperating. This can be thought of as increasing the benefits of cooperating, where a benefit is the avoidance of these costs.

Several biophysical features are important as well. First, the desagues **(RSI4b)** ameliorate upstream-downstream conflicts by supplementing surface-water flows downstream of the acequias that have them, and averting waterlogged soils. Second, the acequias employ a relatively low level of technology **(A9)** to produce and maintain unlined earthen ditches **(RSI4a)** that allow water to percolate into the ground. Normally this could be a disadvantage, and there are arguments made in New Mexico that acequia ditches should be lined to prevent percolation losses. In this context, however, the use of earthen ditches to convey water combines with a strong surface-groundwater connection **(RSL10)** to yield an important storage capacity of the system in the form of groundwater storage **(RSG8)**. This greatly increases the benefits of cooperation, particularly during droughts when surface water is scarce and groundwater can be the only available resource. Finally, many of the acequias have historically had an important common property pasture system **(RSL)**, which provided substantial benefits to acequia farmers through the production of likestock.

Figure 8 displays these relationships using the relationship types described earlier. The arrows pointing to the key variable "High Benefits/Costs" are all labeled necessary. This illustrates that that the effect each variable has on this outcome is non-additive, or that the contributions different variables make are not substitutable. We could not, for example, maintain a particular outcome by replacing the benefits provided by one element with those provided by another. In this context each variable takes on a degree of necessity in producing the outcome.

### 7.2. Provision within acequias

Figure 9 illustrates the acequia provision situation. While the appropriation of water in the acequias involves many individual decisions, provision activities primarily occur within a large group, when the members of an acequia gather for la limpia de la acequia. This is organized and monitored by the mayordomo, who directs his or her members as they clean the debris and clutter that naturally collects in each ditch. Some of the variables that affect the provision situation by increasing the net benefits of provision carry over from the appropriation situation, and their effects on collective-action do as well. Some of the variables do not carry over. The system of decentralized monitoring discussed earlier, for example, is not used to enforce contributions to ditch cleanings. The majority of this monitoring and enforcement is done by the mayordomo, again with the support of the commissioners. The only new component of this action situation is the "appropriation" component. As mentioned before, this is the source of the benefits that are ultimately obtained through appropriation activities.

### 7.3. Diversion and conflict resolution between acequias

Figure 10 illustrates the diversion action situation, which is the second level equivalent to the 1$^{st}$ level appropriation situation; it consists of the decisions made by the mayordomos to divert a particular amount of water into the main ditch of their acequia, determining how much water their members will have available to divert in the appropriation situations. This situation frequently turns into a conflict resolution collective-choice situation if the officers of several acequias have a meeting to determine whether or not they will continue to use the operational diversion rules. Normally they opt to keep the rules as they are.

While most of the important variables at this second level carry over from the first level, there are two features that are uniquely important here. As a result of the presence of the mayordomos and commissioners, the acequia networks are centralized **(GS3a).** They are also modular

**(GS3b)**, and the combination creates a hierarchical structure **(GS3c)** with two levels, one within acequias and one between. Like other hierarchical networks, the acequias link modules with their hubs (highly connected nodes). This feature maintains low numbers of participants (only hubs/officers) involved in resolving collective-action problems at the second governance level between acequias. Network centrality plays an important role in decreasing group size at this level that it does not at the first level. A second feature that is uniquely important at the second level is a connection to the third level through the historical involvement of local courts as the most important governmental entities in resolving inter-acequia conflicts (**GS1a)**.

## 8. Discussion

In this paper I have used a case study to confirm the importance of a subset of the variables known to be relevant in CPR settings. In addition, this paper helps to move this field forward in two ways. It unpacks important biophysical features and explores the interactions between a relatively large number of variables, each to an extent that is still uncommon in this literature.

This paper has also demonstrated the utility of the SES framework, particularly when complemented with a network of action situations, as a critical aid on guiding a single case analysis. It has likewise demonstrated the advantage of a single case analysis in exploring complex interactions among a large set of variables.

Ultimately, however, what we need is not just single cases, but comparative studies. Enabling this is the primary goal of the framework. To facilitate this, studies must measure a common set of variables with the same protocols. While the SES framework has proved useful in providing the potentially relevant variables, it was not as helpful in establishing a protocol for their measurement. The somewhat ad hoc nature of variable measurement is the biggest weakness of this analysis. Standardized measurement of variables is mostly missing across research in CPR management, and it is currently missing from the framework. Therefore, I would advocate further improvement and formalization of the framework, particularly through the establishment of standards for variable measurement. As demonstrated in this special issue, such work is ongoing.

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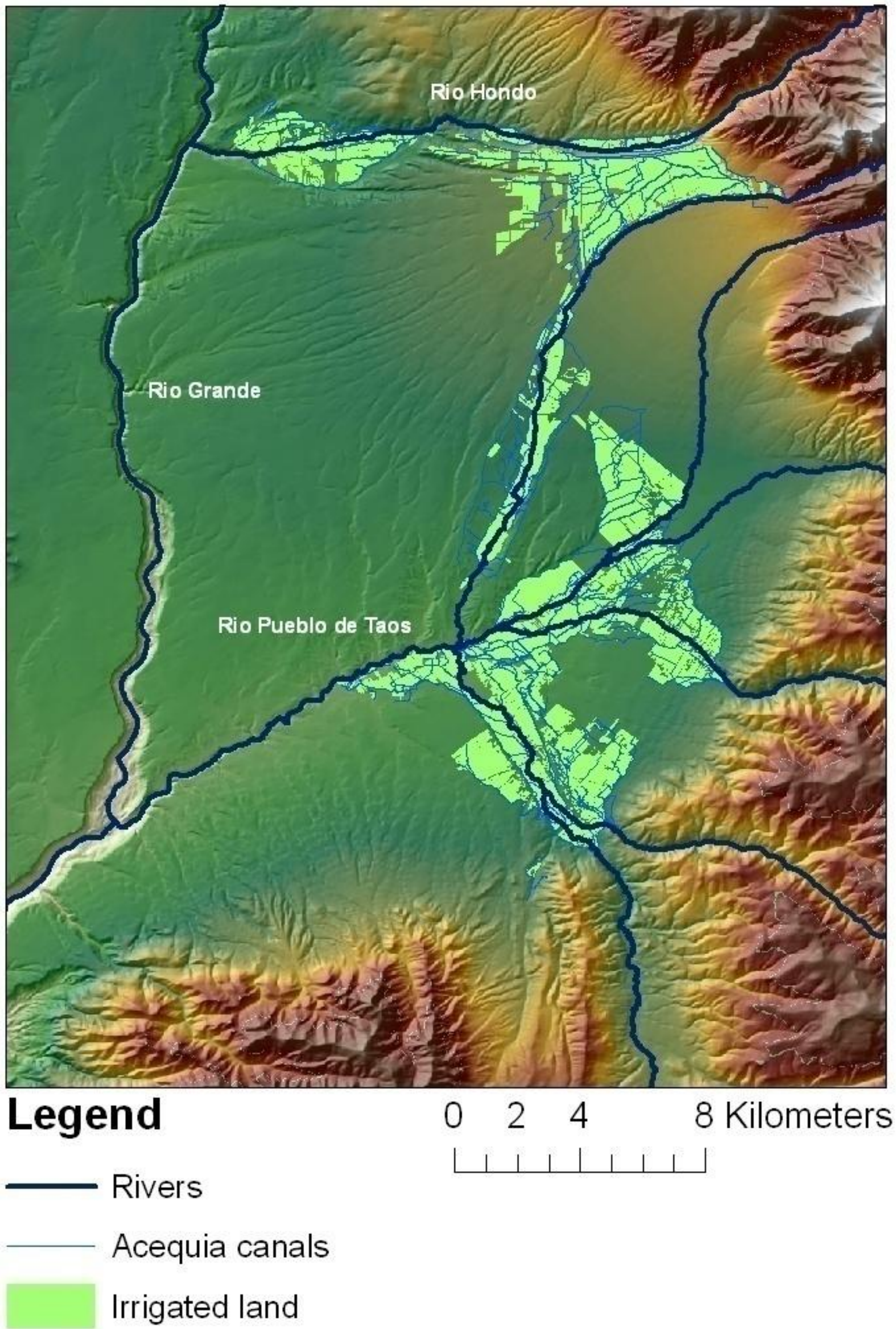


Figure 1: Taos valley

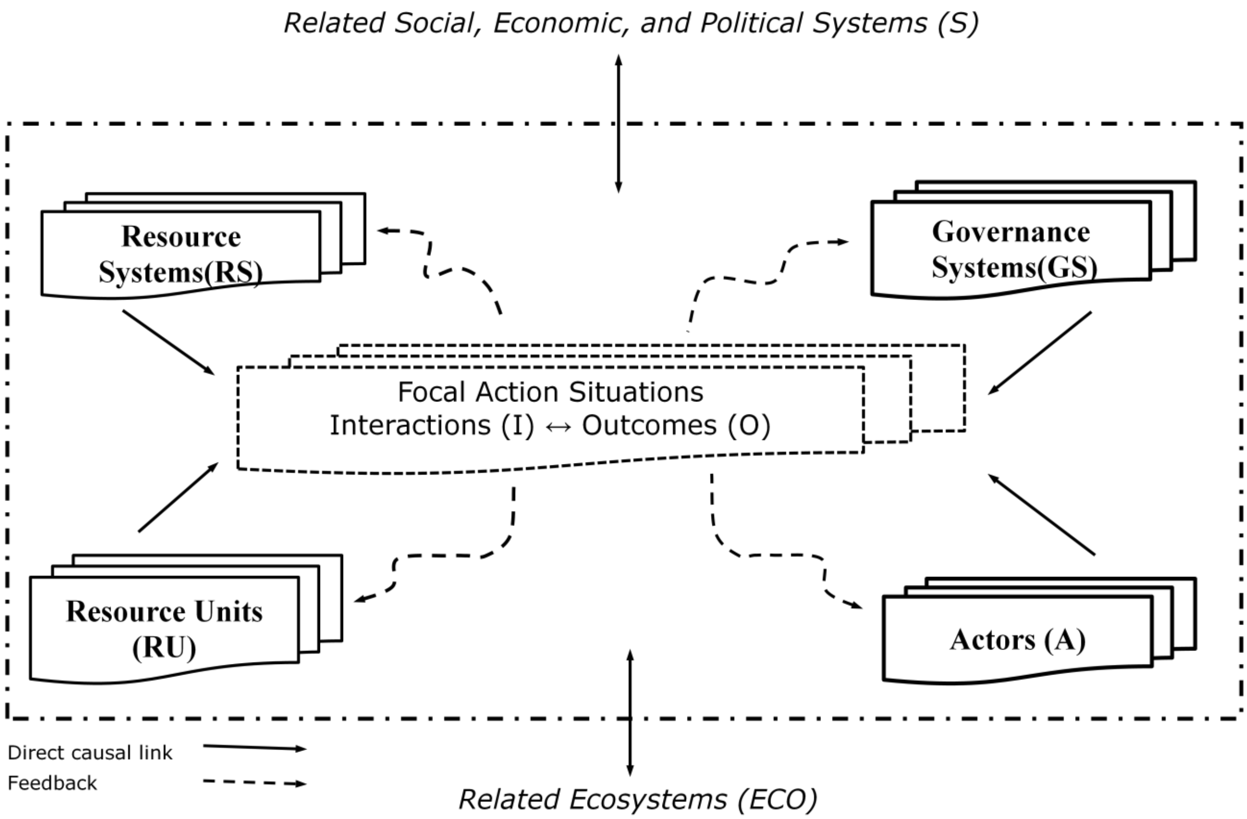


Figure 2: Framework Level one (*Source*: Adapted from McGinnis 2011)

**Social, Economic, and Political Settings (S)**
**S1- Economic development. S2- Demographic trends. S3- Political stability.**
**S4- Government settlement policies. S5- Market availability.**

**Resource System (RS)**

**RS1- Sector (e.g., water, forests, pasture, fish)**
**RS2- Clarity of system boundaries**
**RS3- Size of resource system**
**RS4- Human-constructed facilities**
**RS5- Productivity of system**
**RS6- Equilibrium properties**
**RS7- Predictability of system dynamics**
**RS8- Storage characteristics**
**RS9- Location**

**Governance System (GS)**

**GS1- Government organizations**
**GS2- Non-government organizations**
**GS3- Network structure**
**GS4- Property-rights systems**
**GS5- Operational rules**
**GS6- Collective-choice rules**
**GS7- Constitutional rules**
**GS8- Monitoring and sanctioning processes**

**Resource Units (RU)**

**RU1- Resource unit mobility**
**RU2- Growth or replacement rate**
**RU3- Interaction among resource units**
**RU4- Economic value**
**RU5- Size**
**RU6- Distinctive markings**
**RU7- Spatial and temporal distribution**

**Users (U)**

**U1- Number of users**
**U2- Socioeconomic attributes of users**
**U3- History of use**
**U4- Location**
**U5- Leadership/entrepreneurship**
**U6- Norms/social capital**
**U7- Knowledge of SES/mental models**
**U8- Dependence on resource**
**U9- Technology used**

Action Situation

**Interactions (I) → Outcomes (O)**

**I1- Harvesting levels of diverse users**
**I2- Information sharing among users**
**I3- Deliberation processes**
**I4- Conflicts among users**
**I5- Investment activities**
**I6- Lobbying activities**

**O1- Social performance measures**
**(e.g., efficiency, equity, accountability)**
**O2- Ecological performance measures**
**(e.g., overharvested, resilience, diversity)**
**O3- Externalities to other SESs**
**O4 – Social-ecological equilibrium**

**Related Ecosystems (ECO)**
**ECO1- Climate patterns. ECO2- Pollution patterns.**
**ECO3- Flows into and out of focal SES.**

Figure 3: Level 2 components and properties. (*Source:* Adapted from Ostrom 2007, 15183)

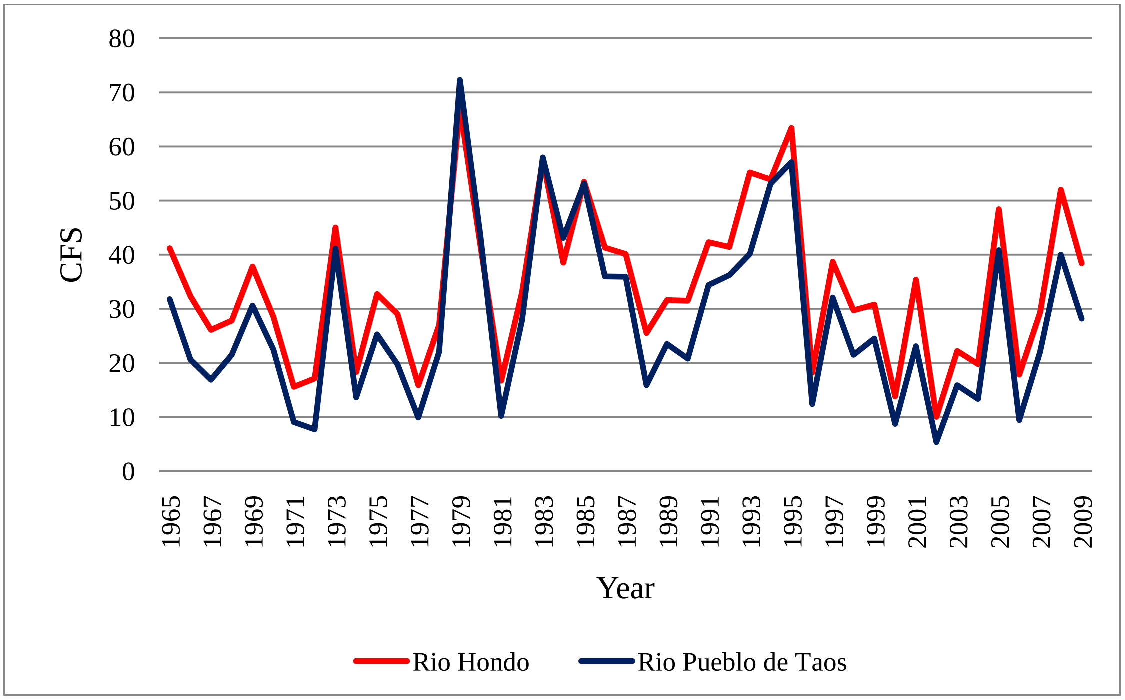


Figure 4: Historical streamflows in the two largest rivers in Taos valley

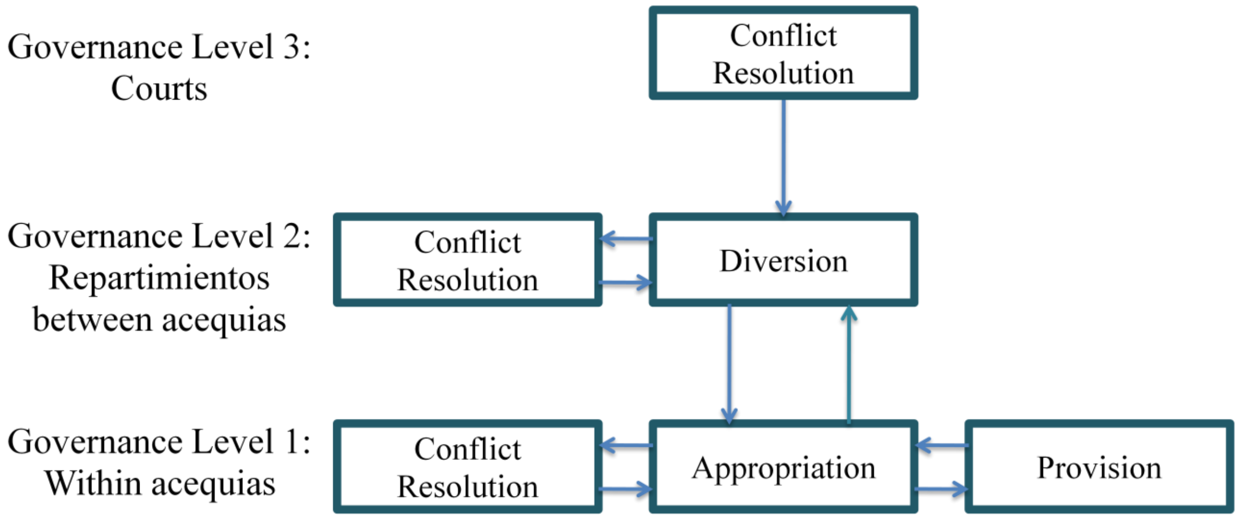


Figure 5: Taos acequia action situation network

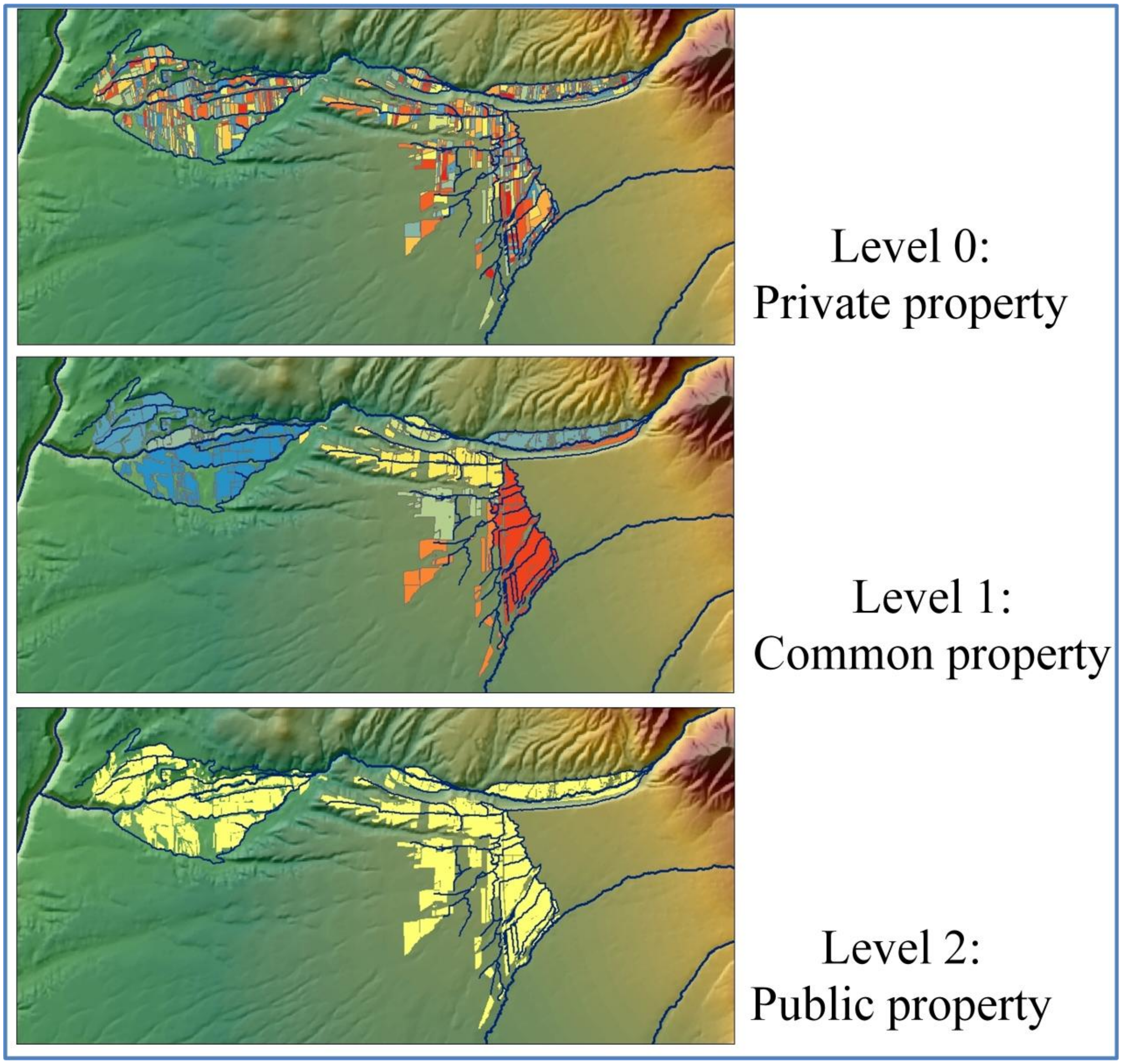


Figure 6: Multiple levels of governance

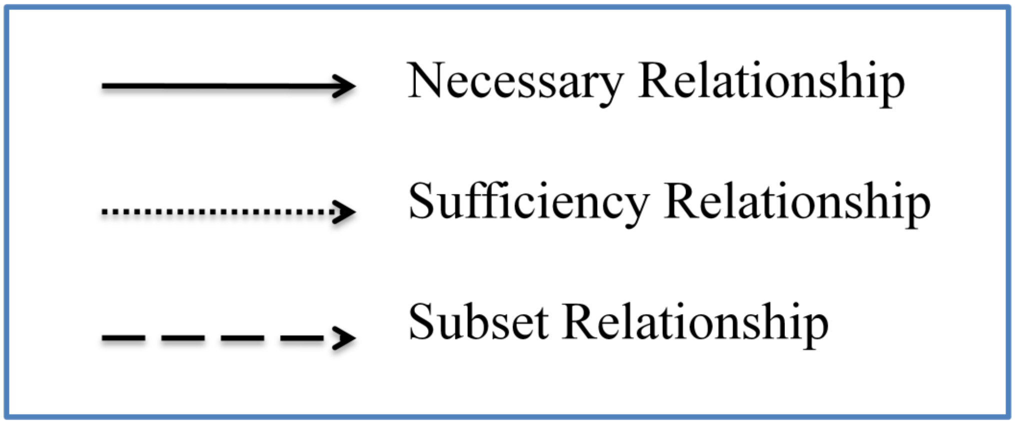


Figure 7: Key to causal diagrams


Figure 8: The acequia appropriation situation

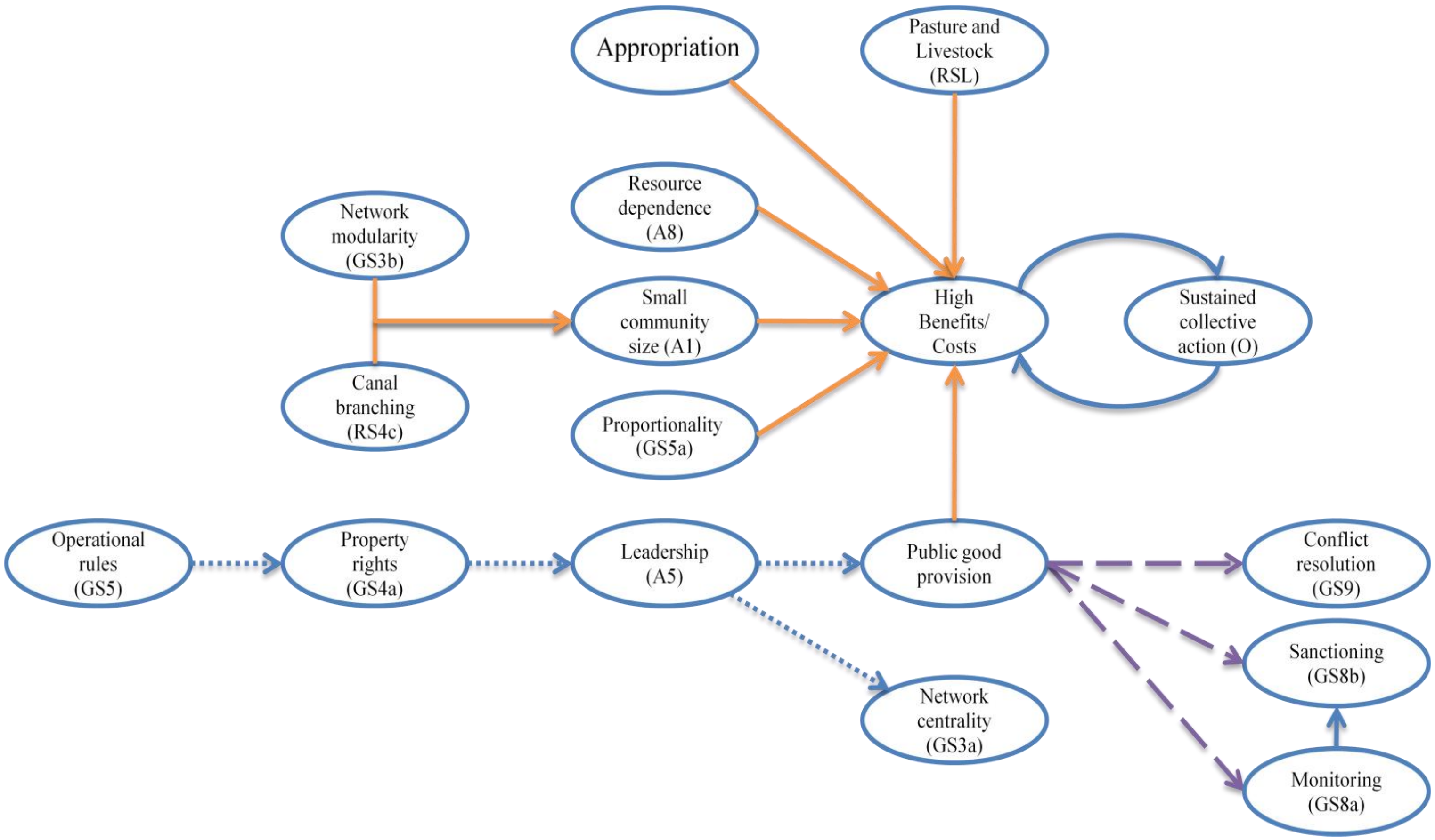


Figure 9: Acequia provision situation

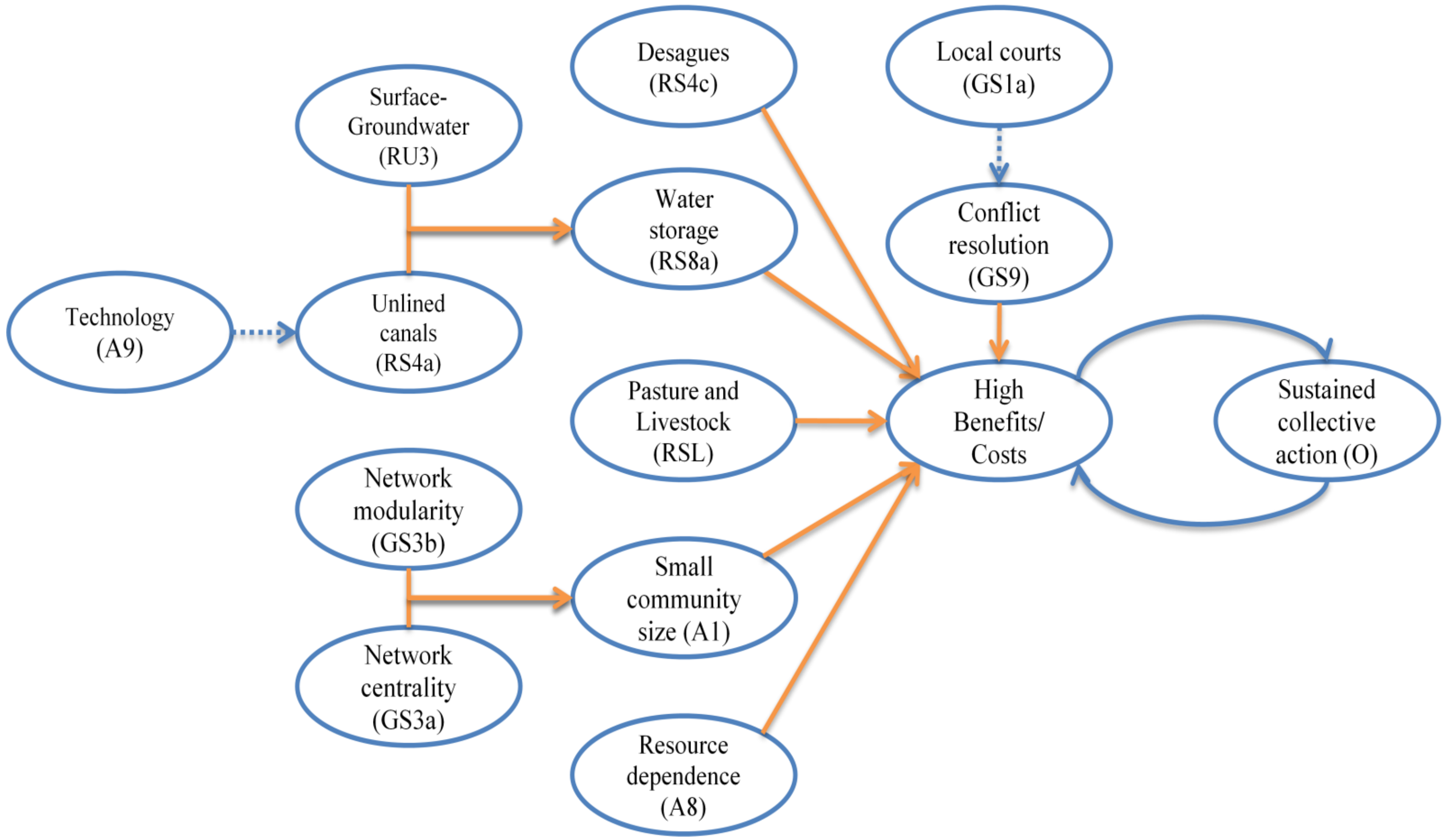


Figure 10: Acequia diversion situation

Table 1: Properties of the Taos acequia SES

| Tier 1 | Tiers 2, 3 | Description | Measurement | Value |
|---|---|---|---|---|
| **Irrigation system** | RSI1 | Sector | Categorical | Irrigation |
| | RSI2 | Physical boundaries | Ordinal | Strong |
| | RS4Ia | Lined or unlined canals | Binary | Unlined canals |
| | RS4Ib | Drainage canals | Binary | Desagues present |
| | RS4Ic | Canal branching | Ordinal | High |
| | RSI7 | Predictability | Ordinal | Low |
| | RSI8 | Storage | Ordinal | Low |
| | RSI9 | Costs of exclusion | Ordinal | High |
| **Aquifer system** | RSG1 | Sector | Categorical | Groundwater aquifers |
| | RSG2 | Physical boundaries | Ordinal | Weak |
| | RSG7 | Predictability | Ordinal | Moderate |
| | RSG8 | Storage | Ordinal | High |
| | RSG9 | Costs of exclusion | Ordinal | High |
| **Land system** | RSL1 | Sector | Categorical | Pasture and agricultural fields |
| | RSL2 | Physical boundaries | Categorical | Moderate |
| | RSL9 | Costs of exclusion | Ordinal | High |
| | RSL10 | Surface/aquifer connection | Ordinal | Strong |
| **Units: Water** | RU1 | Mobility | Ordinal | High |
| | RU2 | Renewability | Ordinal | Moderate |
| | RU7a | Spatial heterogeneity | Ordinal | High |
| | RU7b | Temporal heterogeneity | Ordinal | High |
| | RU8 | Subtractability | Ordinal | Moderate |
| **Governance System** | GS1a | Government organizations | Categorical | Local courts |
| | GS3a | Network Centrality | Ordinal | Moderate |
| | GS3b | Network Modularity | Ordinal | High |
| | GS3c | Network Hierarchy | Ordinal | Moderate |
| | GS4a | Property rights distribution | Categorical | Heterogeneous |
| | GS5a | Proportionality | Ordinal | High |
| | GS5b | Distribution system | Categorical | Rotational |
| | GS8a | Monitoring | Binary | Present |
| | GS8b | Sanctioning | Categorical | Graduated |
| | GS9 | Conflict resolution | Binary | Present |
| **Actors** | A1 | Group size | Ordinal | Low |
| | A2a | Economic status | Ordinal | Low |
| | A4a | Location--Spatial clustering | Ordinal | High |
| | A5 | Leadership | Ordinal | Strong |
| | A8 | Resource dependence | Ordinal | High |
| | A9 | Technology | Ordinal | Low |