Understanding the Acequia Irrigation Communities of New Mexico as Social-Ecological Systems[*]

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1. Introduction

This study is designed to address a practical problem and a theoretical problem. The practical problem is how best to manage irrigation systems so that they sustain themselves and adapt to social and biophysical disturbances. Answering this depends on the development of methods that can capture the dynamics of such systems where humans interact closely with their environment on the earth's surface. The theoretical problem is how to develop the frameworks needed to analyze these human-environment interactions to facilitate an accumulation of scientific knowledge about them.

Two basic approaches have been proposed to address the practical problem: manage irrigation systems from the top-down, in a highly centralized fashion, or manage them from the bottom-up, in a more decentralized, participatory fashion. Over the past two decades, there has been a shift away from centralization towards decentralization and more participatory approaches to irrigation management. This has resulted from noted failures in highly centralized systems and the documentation of many (but by no means all) successful, community-based, decentralized systems. Because of the lack of a coherent theoretical language to analyze human-environment interactions leading to failure or success, however, the theory has lagged behind the field research. We have not fully accounted for why many decentralized systems are sustainable, although we do have many examples of their frequent success (Coward 1979; Wade 1988; Tang 1989; Ostrom 1990; Lam 1998).

This study will address both the practical problem and the theoretical problem by applying an interdisciplinary approach to the community-based, relatively decentralized "acequia" irrigation systems in Northern New Mexico. An acequia is at once the name for an irrigation ditch and for a community of users headed by three elected commissioners and an executive mayordomo. The acequias of New Mexico originated with the immigration of Spanish colonists from Mexico during the 1500s, who brought with them their own irrigation traditions from eastern and southern Spain, and encountered the existent irrigation-oriented culture of the Pueblo Indians already present there (Rivera 1998). The resulting mix of governance institutions has sustained the acequias for over four centuries and through "four major periods of political development in New Mexico: Spanish colonial (1598-1821) Mexican (1821-1848), territorial (1848-1912), and modern (1912-present)" (Rivera 1998, xviii). As such, those still existent today represent presumptively sustainable natural resource management systems. The task then becomes explaining precisely what has enabled them to sustain themselves for so long, as well as to document and explain any failures that may have occurred.

This approach involves several concepts and their related frameworks: social-ecological systems, complex adaptive systems, networks, institutions and collective-action problems. The acequias will be analyzed as joint social-hydrological networks whose structure is a function of their bottom-up management approach, and whose structure in large part has sustained them for the past four hundred years. This study will be guided by testing a set of research hypotheses. These hypotheses result from the interaction of several disciplines, which will be described in the subsequent sections in order to unpack their significance and how they may be tested. Figure 1 is a schematic of the joint social-hydrological network based on these hypotheses and the discussion of them that follows. The hypotheses are:

1. The institutions that govern the acequias and embody their successful collective-actions support established theories regarding successful collective-action in community-based natural resource governance, particularly the design principles developed by Ostrom (1990).

2. The hydrological network of the acequias is a scale-free hierarchical branching network, with nodes that cluster geographically.

3. Two social nodes are more likely to be socially linked through the resolution of a collective-action problem if their corresponding hydrological nodes are in close geographic proximity to each other.

4. Consequently, the social network in the irrigation system will be scale-free and modular, with the density of links between social nodes positively related to their geographic proximity.

5. The network topology of the social system and its relationship to the hydrological system sustains the acequias in two ways: (1) by facilitating manageable resolution of localized collective-action problems within acequias, and (2) by giving acequias a mechanism to resolve higher-level collective-action problems and access to physical resources such as water, food, or labor to help sustain them when they face disturbances.

The first hypothesis ties the network analysis to *institutional analysis* (Ostrom 2005) and the theories developed regarding successful community-based natural resource governance. The second three hypotheses relate the social and hydrological network structure of the acequias to their decentralized generation and management. The fifth hypothesis relates this structure to the sustainability and adaptability of the acequias to disturbances.

These hypotheses are probabilistic rather than deterministic: bottom-up management is not hypothesized to universally lead to particular network structures or institutions, and these structures and institutions are not presumed to guarantee sustainability. Given the complexity of human-environment interactions, such determinism is untenable. Rather, each hypothesis relies on a theoretical mechanism for the relationship it posits, which when combined with an empirical test, yields contingent and probabilistic, but still useful, theory regarding human-environment interactions in community-managed irrigation systems.

2. Theoretical background

2.1 Collective-action problems

The concept of a collective-action problem is central to these hypotheses and the social, hydrological and geographic distributions of the acequias as social-hydrological networks. A collective-action problem is a divergence between individual and community interests, where the pursuit of individual gain is collectively harmful. In order for a community to function, it must resolve collective-action problems. There is an established literature on collective-action problems that relates their occurrence to the management of common-pool resources such as irrigation systems (Tang 1989; Ostrom 1990; NRC 2002). The presumption that irrigators are unable to resolve these collective-action problems is a part of a general set of arguments related to the "tragedy of the commons" in natural resource management (Hardin 1968), most famously applied to irrigation by Karl Wittfogel (1957). For many years, these arguments have been used to justify a more top-down management approach to irrigation.

The source of a collective-action problem in an irrigation system theoretically results because of its properties as a common-pool resource. A common-pool resource is defined by two properties: cost of exclusion and subtractability of use, meaning that it is difficult to exclude potential users from consuming the resource, and one person's consumption subtracts from the amount available to others. These properties lead to at least two types of collective-action problems in irrigation systems and other common-pool resources: those of appropriation and provision (Ostrom et al. 1994). In both cases the conflict arises because what is in the interest of each individual resource user is not what is optimal for the community.

Appropriation is the consumption of a resource unit; provision is labor applied to the infrastructure that makes the resource available, such as an irrigation headworks. An appropriating resource user benefits from using irrigation water while not incurring the full costs of that appropriation, so what is individually optimal is not socially optimal. These costs result because water use is subtractable: what one uses is not available to another. In economic terms, an overappropriating irrigator imposes a negative externality on the remainder of the community. To effectively manage an irrigation system, upstream users must be prevented from overappropriating water so that some is available to downstream users.

With resource provision, the user is effectively supplying a positive externality to the community while not receiving the full benefits of his or her labor. In an irrigation system, this labor is put towards maintaining the physical infrastructure such as canals and diversions. The conflict arises because it is difficult to exclude other irrigators from enjoying the benefits of one's labor towards maintaining the infrastructure of the irrigation system, which lowers the incentives for those others to contribute labor themselves. This can lead to low levels of infrastructure maintenance. In this case, incentives must be provided to irrigators so that they will cooperate to maintain the infrastructure by contributing labor at a level which is socially optimal but not individually optimal. In order for a community to effectively manage an irrigation system, both appropriation and provision problems must be resolved so that water is not overappropriated and the infrastructure is maintained. How these collective-action problems are resolved will, in turn, affect the network structure of the system and the outcomes that it achieves.

2.2 Integrating the frameworks

2.2.1 Background

The frameworks of social-ecological systems, networks, and institutional analysis can be integrated by their inherence in the broader framework of complex adaptive systems. We may define a social-ecological system as social system "in which some of the interdependent relationships among humans are mediated through interactions with biophysical and non-human biological units" (Anderies et al. 2004). With this definition irrigation systems are clearly social-ecological systems, where the interactions between humans are mediated by the water that flows (or does not flow) between their diversions.

A social-ecological irrigation system can usefully be viewed as a social-hydrological network. Janssen et al (2006) propose that viewing social-ecological systems as networks with both human and non-human nodes is a useful way to move forward with the goal of relating structure to outcomes in comparable systems. "A network perspective might be a useful complement to existing analysis because it focuses explicitly on the structure of the interactions between the components of social-ecological systems and the ways in which this structure affects the performance of the system. Another benefit of a network perspective is the availability of a uniform language with which to describe complex systems in terms of nodes and links". In a social-hydrological network there are both social nodes and hydrological nodes, with three types of links: social to social links, hydrological to hydrological links, and social to hydrological links.

This basic framework can be further complemented by representing it as a complex adaptive system. The notion of a complex adaptive system (CAS) I have in mind here is taken directly from John Holland (1995b), who identifies four basic characteristics of a CAS. These and related terms are presented below.

1) Diversity: Functional heterogeneity between the elements within a system
    a. Variation
    b. Evolution: Natural selection resulting from the interaction between a diverse population and its environment
    c. Adaptability: Capacity to change system behavior in order to survive or maintain desired properties in the face of novel environmental pressures
2) Aggregation: The arrangement of systems at hierarchical levels of aggregation, each with properties and functions that are not reducible to those exhibited at other levels
    a. Hierarchy
    b. Emergence: The process whereby the properties of elements on a given level of a complex system are irreducible to the properties of elements on a previous or lower level. Such properties are called *emergent properties*.
    c. Near-Decomponsability: The property that elements within one level have more frequent flows occurring between them than between any of them and elements at a higher level
    d. Scale: When used relative to a hierarchical system is analogous to a specification of a certain level of the system. More generally, primary forms may be dimensional (space, time), structural-functional, or conceptual.
3) Flows: Transfers of matter and/or energy (often in the form of what could be called *information*) between components of a system either directly (within one scale) or indirectly (across scales)
    a. Flux
    b. Matter: One primary component of the substance of flows
    c. Energy and Information: Energy, together with matter is the basic component of any flow; depending on the existence of a complex receiver, may also be considered to take the form of information
    d. Gradient: Change in a variable quantity, such as density, temperature or pressure, over some distance. We most commonly understand the mechanism that induces natural flows as a flattening-out of gradients (ex. concentration gradients and diffusion; available energy gradients and the second law of thermodynamics)
4) Nonlinearity: Non-constant rate of change between a cause and its effect. It is often described as a characteristic of a CAS insofar as the behavior or properties at one level are not simply the sum of those of elements at a lower level.
    a. Feedback: May be positive or negative, where positive indicates a self-reinforcing process, and negative indicates a self-inhibiting process
    b. Irreversibility: Characterizes situations where positive feedback raises the costs of returning to a former system state
    c. Uncertainty: Ubiquitous characteristic of complex systems that result from nonlinear changes in parameters and functional dynamics (see Wilson 2002)
    d. Ergodicity: "an ergodic stochastic process simply means that average calculated from past observations cannot be persistently different from the time average of future outcomes" (North 2005, 19). Because of nonlinearity, and specifically positive feedback, complex adaptive systems are non-ergodic.

Each of the concepts above is important for understanding complex social-hydrological irrigation systems and the collective-action problems they confront. While a more complete discussion will be presented in the dissertation, the properties of aggregation and emergence are particularly important for this discussion. Emergence occurs when the interaction of components in a complex system yields system-level properties that are conceptually independent of the properties of the components. These system-level properties are called emergent properties[1].

2.2.2 Institutions and hypothesis one

The first hypothesis states that the institutions in use within the existent acequias reflect the theory that has so far been constructed that relates institutions to sustainable common-pool resource management (NRC 2002; Ostrom 1990). Institutions[2] I believe can usefully be described as emergent properties of a community resulting from the individual-level adaptations[3] of participants in that community within a common setting that allows a shared understanding of those institutions to develop.

Institutions then are the structure of a community that embodies the resolution of collective-action problems it faces. Individual-level adherence to community institutions is what allows that community to functioning meaningfully as a group and not just a collection of individuals. Institutions are emergent social phenomena that result from the interactions of individuals: institutions “depend upon the thoughts and activities of individuals but are not reducible to them” (Hodgson 2006, 2).

This point emphasizes the complementarity between institutional and network analysis, in that both emphasize recording the interactions between participants rather than simply their individual-level attributes, although these still are important, as the literature on institutions for successful natural resource management have emphasized (NRC 2002). Because of this complementarity and the intimate connection between institutions and social links between participants the construction of the social network model and the recording of institutions will be contemporaneous with each other in this project. Moreover, as a result of this I will be able to compare the institutions that are in use within the acequias both with established theory for successful community-based natural resource management and with the social network structure that reveals itself to further explain their success, or failure.

2.3 Social-hydrological networks

2.3.1 Hypothesis two

The geographical distribution of hydrological nodes and the links between them in the system is not random, which would imply that there is no geographic clustering of nodes, and that each node has an equal chance to be linked to any other node. In the case of the acequias in

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[1] Emergent properties are relational in the sense that an emergent property reflects the relations between the components in the system whose interactions produce it. The most important type of emergent properties to consider are what Bar-Yam (2003) refers to as *global* emergent properties, or those that vary with the spatial scale of the system. In physics these are referred to as extensive (as opposed to intensive) properties.

[2] I have in mind here primarily institutions-in-use as opposed to institutions-in-form, which do not necessarily evolve.

[3] Adaptations in the form of behavioral rules, generally of the form *do X if Y*, where a behavioral rule signifies that the probability of behavior X is greater in the presence of environmental condition Y than it is without that condition

New Mexico, the incremental bottom-up processes that developed the system over several centuries has led to a distribution of nodes and links that is non-random.

A bottom-up constructed irrigation system is similar to many other natural and man-made networks that grow incrementally and serve to provide a resource, such as oxygen, nutrients, electricity, or water, to a set of consumers, referred to generally as hierarchical branching networks (West and Brown 2004). In these systems, a network of flows connects a set of nodes to a source of that flow. Some of the basic properties of these systems developed in network theory are relevant for studying irrigation systems. First, the network is unidirectional with respect to the flow of the resource, which originates at a particular source or network hub. In an irrigation system, this hub is the initial diversion structure off of a river, or headworks. This node is at the top of the hierarchy, with nodes directly attached to it one step down, and nodes that link to them one step farther down, and so on.

The significance of the term "hierarchy" in the description of the hydrological network that results from bottom-up management is not synonymous with the hierarchical arrangements implied by top-down control. The central theme of the four hypotheses listed earlier is that the structure and outcomes in the acequias result from bottom-up management, where decisions are made incrementally by individual irrigators whose interactions then build up to determine structure and outcomes at larger scales. The types of hierarchies and centralities that are to be found in both their social and hydrological network structures are qualitatively different than what would result from a conscious design of the entire system by a centralized authority (Barabasi 2000). In bureaucratically centralized systems, hierarchy is more unidirectional, emanating from the top down with less feedback from the bottom to the top, and centrality is much higher (Lam 1998). In systems like the acequias, this hierarchy and centrality emerge from lower-level interactions between actors who do not consciously design the larger system but make decisions each from their own perspective.

The growth of the hydrological network involves new headworks off the river that serve as hubs and the accumulation of lower-level diversions off of the canal that each headworks feeds. The creation of headworks is more costly than a small downstream diversion, and requires teamwork to build and maintain. Thus, it is less costly to build diversions off of a main canal than to build an entirely new headworks structure directly off the river, and this will lead irrigators to build incrementally off of this main canal until the flow from it is exhausted before an additional headworks is constructed. This leads to the branching quality of the hydrological network, with each branch being a canal that feeds directly off of a river from a headworks.

Within a branch, flow volume and the geographic length of the downstream canal or link both generally decrease with each level on the hierarchy: the main canal off a river will generally be longer and have greater volume than a tertiary canal, for example. The lower flows result because each diversion takes a portion, but not all, of the flow from where it diverts. This results in shorter downstream canals and streams because each canal used to irrigate in an arid environment is generally a losing or influent stream, meaning that it loses water along its length (Task Committee on Hydrology Handbook 1996). With lower flows, there is less water to lose and what is available is exhausted in a shorter distance. This shorter length means that diversions on lower levels of the hierarchy will cluster together geographically, because the length of the canals separating them is shorter.

Because of the higher volume near the hub, the incremental growth within a branch will display what Barabasi (2000) refers to as "preferential attachment." where the larger an existent node is, the more like it is that a new node will connect to it rather than a new, smaller, less connected node. This is simply because the downstream flow from the original node is larger and has more water to support new diversions off it than do subsequent canals with lower flows. Eventually, the flow is exhaustively consumed by evapotranspiration and groundwater seepage, and no further branching can be supported.

Defining the link between two hydrological nodes as an upstream-downstream relationship, this yields a "scale-free" hydrological network within each branch off of the river, which is characterized by an unequal distribution of links between nodes, with one or several hubs having many more links than the average node in the network. Moreover, because the length decreases with each subsequent diversion, the hydrological nodes will be spatially clustered within branches across the geographic area of the irrigation system.

2.3.2 Hypothesis three

The third hypothesis states that the nearer two hydrological nodes are to each other, the more likely their two associated social nodes will be linked. The association between a social node and a hydrological node occurs because at the bottom of the hierarchy in the hydrological network, each hydrological node is a diversion that irrigates the fields of one particular irrigator.

The nearer two hydrological nodes at the bottom of the network hierarchy are, the more likely it is that they are both downstream of the same larger hub and within the same hydrological branch. This means that their associated social nodes are also both downstream of this hub, and these irrigators need to work together to maintain the main headworks they each ultimately depend on. Thus, when a set of geographically proximate irrigators share an interest in maintaining a particular hydrological hub, they have increased incentives to resolve with each other the collective problems involved in managing an irrigation system.

Additionally, the geographic proximity of the social nodes makes their interrelatedness more visually obvious and salient, and the proximity of their associated hydrological nodes sets natural boundaries on the portion of the larger irrigation system they to which they belong. With these boundaries, the chances for successful local collective-action to successfully manage the resource are improved (Ostrom 1990). The resolution of these collective-action problems creates social links between the irrigators involved. While these irrigators may be hydrologically connected to other irrigators outside of this more immediate community, these connections are not as immediate or salient.

2.3.3 Hypothesis four

Barabasi (2000) notes that in addition to being scale-free most real networks are modular. The fourth hypothesis states that as a result of the second and third hypotheses, the structure of the social network will be modular and scale-free. Each community, or acequia in New Mexico, then forms a module in part of a larger modular social network. Herbert Simon (1962) proposed this property with respect to complex systems generally but referred to the structural characteristic as *near-decomposability*. In both cases, it refers to the arrangement of a system into subgroups, or modules, whose processes and functions are relatively independent of the functions of other modules, although each of which may be contributing to the function of the larger system or network. In the case of a bottom-up managed irrigation system, the social modules are communities of irrigators with common upstream headworks and geographically proximate diversions who have resolved a set of collective problems and come to a common understanding of what institutions are to guide their interdependent behaviors. With greater link density within modules than between, the density of the social network then reflects the geographic clustering of the hydrological links.

Different acequias or modules are also hydrologically and socially connected. Some acequias are downstream of others, and members in one acequia do communicate with members from another acequia with or without hydrological links. This communication between modules occurs through social hubs, or highly connected social nodes, which also give the network its scale-free structure. Newman and Dale (2005, r2:1) distinguish between the links within a module and between modules in a social network as "bonding" and "bridging" connections: "Bonding ties are relations between family members, friends, and neighbors in closed, tightly connected networks. Bridging ties give access to resources and opportunities that exist in one network to a member of another network."

2.3.4 Hypothesis five

The fifth hypothesis relates the network structure that results from bottom-up management to propose why this approach tends to enhance the probability of sustainable outcomes in irrigation systems. To explore this hypothesis, a conception of sustainability has to be established. One basic indicator for sustainability that will be used in this study is longevity. With historical evidence documenting the existence of the acequias in the study area for several hundred years, based on this initial indicator they are sustainable. The analytical task then becomes documenting their social-hydrological network structure to reveal how it has helped them to persist, and if some have not, why not.

Answering the question of system failure is aided by identifying a disturbance to the system as a possible cause for failure. Besides the basic notion of being persistent through time, within the social-ecological system literature sustainability has been linked to two other concepts, both of which deal with adaptation to disturbances: resilience and robustness. The concept of resilience comes from ecology, while the concept of robustness comes from engineering. Resilience can be defined as "a measure of the persistence of systems and their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" (Holling 1973, 14), while robustness is defined as "the maintenance of some desired system characteristics despite fluctuations in the behavior of its component parts or its environment" (Carlson and Doyle 2002, 2539). Both concepts relate to the ability of a system to adapt to disturbances in order to maintain important relationships and functions. From this framework comes sustainability as adaptability. In this study, sustainability indicated by both longevity and adaptability will be considered. The two conceptualizations are complementary, but imply different analytical methods, which will be addressed in the methodology section.

The modularity of the larger system of groups of acequias is sustainable in part because it economizes on the informational load required of any particular irrigator. Resolving collective-action problems requires participants to establish a common understanding and expectations regarding the actions and reactions of other participants. This becomes increasingly difficult to maintain if the number of participants increases. Within the literature on community-based CPR management, it is commonly remarked that smaller systems enjoy comparative advantages over larger ones in their ability to successfully act collectively (Baland and Platteau 1996).

With fewer members, the relationship between a particular participant's actions and the outcomes in the system is more easily identified. This allows for participants to react to each other based on information of each other's past actions and concomitant reputations, and facilitates better compliance with and enforcement of community rules. Moreover, each acequia represents a principal-agent problem (Eisenhardt 1989) when the mayordomo is selected to manage the diversions of the system. The principals are the parciantes and the agent is the mayordomo. The information asymmetry is lessened in a smaller system for similar reasons because the parciantes have more information regarding the actions of the mayordomo and how these relate to the outcomes the parciantes experience. Better information allows the parciantes to better hold the mayordomo accountable and resolve the principal-agent problem. Thus, while there are asymmetries of information and power within the acequias, these are of a smaller degree than would occur in a large state-managed system.

Instead of having to solve one giant collective-action problem and the high levels of information asymmetry that would result, a modular social system can effectively resolve many smaller and more manageable collective-action problems. This autonomy then allows individual acequias to act and adapt to local disturbances without having to consult with an excessive number of external participants. The larger irrigation system effectively becomes a serial processing system.

These local adaptations within autonomous modules can then be integrated by the "bridging" links between acequias. These bridging connections give the network a property that Janssen et al. (2006) refer to as "reachability" or the extent to which any given node is ultimately connected to any other node, however indirectly. This reachability in the modular network is accomplished by the fact that it is also scale-free, or contains hubs: nodes with higher-than-average numbers of links. These hubs are the nodes that are densely connected within a module but also contain connections to other modules--in the case of this study, other acequias.

There are several adaptive advantages of reachability. Bodin et al. (2006) argue that this quality allows for the system to develop a collective memory of the experiences of individual modules, which may aid in its ability to adapt based on the experiences of success or failure of different acequias. Additionally, this reachability may be used as a flow of physical resources such as food, water, or labor in order to help an acequia sustain itself through a disturbance such as a drought. Thus, the reachability of the larger network may increase the adaptability of an acequia within that network. This possibility also depends on hydrological reachability of the acequias if they are to share water. In Taos Valley, New Mexico, the sharing of water in times of need between those who have more and those who have less is a common practice (Rodriguez 2007). Baker (2005) makes the argument that reachability across irrigation communities is a critically important property that has helped certain Kuhl irrigation communities in the Himalayan Mountains sustain themselves through various disturbances by sharing resources between networks.

3. Analytical methods

There are four basic sources of data that will be used for this dissertation. The first are spatial data to be integrated with GIS software (ArcMap). The second are historical documents such as court orders and rulings. The third are historical time series data of biophysical conditions in the study areas. The fourth are interview data that I will co-produce with interviewees.

Using existing data, the social and hydrological network models will be constructed for a selected study area. Following this, a set of acequias will be selected for more in-depth study involving physical tours of the system and semi-structured interviews with irrigators. This will allow for more precise indicators of the social and hydrological links in the networks and to check the validity of the indicators based on existing data used to construct the networks for the rest of the study area.

3.1 Study sites

There are several possible study sites that could be used for this dissertation. The two described here are chosen because of the personal contacts I have there and because of data availability. These are each circled in the New Mexico map in figure 2. Acequias along the Rio Chama and along the Gallinas River are also notable for similar reasons. The descriptions of methods in the sections that follow describe the research as it would occur in Taos, but similar methods would be used in alternative study sites.

3.1.1 Taos Valley

The Taos Valley contains a high concentration of traditionally operating acequia systems, with the Taos Valley Acequia Association being the largest such association in the state. Additionally, there is a large amount of data available on the irrigation systems in this valley, in part because of a state-run water rights adjudication that is ongoing there. Efforts to collect social and hydrological data have been conducted as part of the data collection for this suit, much of which is publically available and will be used in this study.

The Taos Valley is bordered by the Sangre de Cristo Mountains on the east and the Rio Grande on the west, generally sloping downwards from east to west. With only twelve to fourteen inches of rain each year in the valley, the sources of irrigation water for the acequias in the valley come primarily from rivers that carry snowmelt from the Sangre de Cristo Mountains. These rivers ultimately become tributaries to the Rio Grande. The main use of water in the valley is irrigation; the other main water users in the valley besides the acequias are the Taos Pueblo Indian community and the growing municipality of Taos.

3.1.2 Alcalde

Each of these ditches diverts water from the Rio Grande itself, and as such their hydrological positions and relationships are quite different than those in the Taos Valley. They do not rely as directly on snowmelt, and because of the comparative size of the Rio Grande, they do not experience the severity of water conflicts that the acequias in Taos Valley does. Alcalde is additionally interesting because of the location of the Sustainable Agriculture Science Center there as a research center from New Mexico State University. Here several important experiments have been conducted recording the surface-groundwater relationships in the acequias (Fernald, Baker, and Guldan 2006). The location of this facility there and the contacts I have through it would help with data collection for an analysis.

3.2 Integrating the social and hydrological networks

Each node in both networks will be defined by their geographic location (latitude, longitude), their links with other nodes, as well as attribute data such as the size of a diversion, or the age, sex, and length of residence of an irrigator. The links in the hydrological network will be defined by their length, average width and flow when available, influence or effluence, and whether or not they are irrigation return flows. The links in the social network will be defined by the geographic distance between the social nodes and the type of interaction between them, which will be defined later.

The social and hydrological networks will be spatially integrated into a Geographic Information System along with other publically available GIS data on the study area, such as demographics and land use. After this, structural variables of the social and hydrological networks will be calculated in order to test the research hypotheses.

3.3 Constructing a geographic model of the hydrological network in Taos Valley

The nodes in the hydrological network consist of natural and man-made diversions within the study area, while the links are surface-water flows between nodes. When it is hydrologically and socially important groundwater interactions will be included as well. To my knowledge there do not exist maps of the whole valley that include all individual-level diversions, but the Office of the State Engineer does have maps that trace the geographic extent of each acequia. There exists a large amount of data regarding the hydrological and biophysical properties in Taos Valley. This includes complementary surface-water (Bellinger 2003) and groundwater (Barroll and Burck 2006) hydrological models that were conjunctively developed, as well as hydrological, elevation, land use, vegetation, and soil type data in GIS format. With respect to Taos Valley the office of the State Engineer has available more than one hundred maps from hydrographic surveys that portray the geographic extent of particular acequias within the system and their summary statistics. Finally, NASA's landsat remote sensing database contains monthly satellite images of the study areas dating back to the early 1980's, although due to expenses only a few of these images will be obtained.

These data will be used to create the hydrological nodes and to characterize the links between them. The list of nodes and their links will initially be populated using the nodes and links schematically presented within the surface-water model (Bellinger 2003), which includes the major acequias and their diversions in the entire valley. These will be integrated with data on the study area from the National Hydrological Dataset from the USGS and the other available data to create a basic GIS-based hydrological network model of the study area. The combination of these data will allow for testing of the first hypothesis regarding the structure of the hydrological network, and will help describe the hydrological relationships between irrigators that interact with their social organization.

3.4 Constructing a geographic model of the social network in Taos Valley

The nodes in the social network are the individual irrigators. Several existing data sources will be used to construct the nodes and their geographic locations within the social network. The recording of the social nodes has already been conducted by the government of Taos County, and the social network construction will start with this initial list of irrigators.

Additionally, the Office of the State Engineer has recorded information on each acequia in the river, including its name, number of irrigators, address, and total acres irrigated as of 1987 (Saavedra 1987) and the Office of the State Engineer has hydrgraphic survey maps that include these acequias. Finally, the county government is actively involved in putting their property rights database into a Geographic Information System, which would facilitate the determination of the geographic locations of the social nodes in the system. These geographic locations will be placed at the confluence of the irrigators' diversions and their agricultural fields.

Determining the presence of a link between social nodes is less visually obvious than determining the link between hydrological nodes, which is based primarily on surface-water flow. Determining what counts as a link between two irrigators depends on what aspect of a social relationship is important for the functioning of the irrigation system.

Two types of data will be used to determine the links between social nodes. The first type is existing documentation of participation by irrigators in collective activities. Within an acequia, this includes the attendance at the annual spring ditch cleaning, as well as other cleanings of ditches as they are needed; it also includes local elections of the three commissioners and the mayordomo who formally govern the acequia. This type of information is frequently kept in the logs of the mayordomo who acts as the executive officer of the acequia. Between acequias, there is less formal participation to be documented, but this does include membership in three regional religious parishes that geographically cover most of the extent of Taos Valley.

The second type of data will come from in-depth open-ended interviews with irrigators in the selected subset of acequias, as well as with members of the Taos Valley Acequia Association and the regional Taos County Government. An example of the methodology to be used in conducting the interviews is shown in the study by Isaac et al. (2007) in their analysis of farmer networks in Ghana. Irrigators will be asked a set of questions regarding who they associate with on a regular basis in the context of the management of the irrigation system, as well as who they may associate with on a less formal basis. Questions will also be asked about the exchange of emergency help during times of sickness, financial need, or accident. Three basic social link types will be considered to help guide these interviews as well as the interpretation of the archival data that is available:

Relational: Two irrigators both attend the same meeting, event, or social function that is indicative of a social connection between them.

Transactional: Two irrigators engage in a very broadly defined exchange relationship, in which one or both does something that benefits the physical well-being of the other. This could be the contribution of labor to the irrigation works, the sharing of water by closing one's gate so a downstream irrigator my use it, or giving support when one faces a family emergency.

Authority: One irrigator, frequently the mayordomo, acts as a source of authority over the actions of another irrigator, most commonly in the form of monitoring behavior and sanctioning infractions of established rules within an acequia. Authority links are directional links.

3.5 Measuring Sustainability

Using longevity as one indicator for sustainability, we already know that the existent acequias are sustainable since they have persisted in northern New Mexico for over four hundred years. The task here then becomes documenting the structure of the acequias and relating this to their ability to resolve collective problems in order to maintain the needed physical infrastructure and avoid overappropriations.

Measuring sustainability as adaptability requires further analysis. First, it requires measuring the incidence of a disturbance to the system. There are two main types of disturbances that will be studied: social and hydrological. The following is a list of the disturbances that will be considered:

1. Biophysical
    a. Droughts (historical time-series data)
    b. Floods (historical time-series data)
    c. Pests and plant diseases
2. Social
    a. Market penetration and developmental pressures
    b. External governmental involvement
    c. Price fluctuations
        i. Input prices for irrigation and agricultural products
        ii. Wages paid for and continued availability non-farm jobs
    d. Endogenous shocks (ex. Leadership turnover)

The hydrological disturbances will be based on both qualitative accounts in interviews with irrigators as well as historical data on precipitation in the study area and USGS monthly stream-flow data that is available for all the rivers in the area, several dating back to 1913 and continuing to the present. These data, along with historical precipitation data from the US National Climatic Data Center, will be used to determine when a disturbance has occurred based on standard metrics for different types of floods and droughts that have been developed (Dingman 2002). Moreover, with GIS software (ArcHydro) these time-series data can be related to particular reaches within the irrigation system. These quantitative measurements will be checked during interviews with historical accounts of possible disturbances as perceived by the irrigators themselves. The incidence of social disturbances will be documented based on interviews with the irrigators and other local participants in the systems as they perceived them.

Interviewees, in addition to being asked questions regarding the incidence of disturbances to the system, will be asked to account for how the system responded and what outcomes resulted: who worked with who, and where, and how well the system maintained itself. Insofar as disturbances and responses are a function of network links, this data collection will be contemporaneous with the construction of the social and hydrological models. Outcomes of success or failure will be recorded as the interviewees perceived them, and these responses and outcomes will be related to the social-hydrological network structure of the systems. A model for this type of analysis is found in Sylvia Rodriguez's (2007, 68-72) brief account of a severe drought in the valley in 1996, in which she details, based on interview data, the response of the system.

3.6 Research Structure

The study will encompass eighteen months, which can be divided into six phases, three of which are trips to the study site for data collection, and three of which follow a fieldwork phase and involve data organization, analysis, and write-ups.

Phase one: Three-month field trip to New Mexico for data collection in the study area. Interviews will be conducted with irrigators, scholars, and local government officials in order to construct the social and hydrological network models.

Phase two: Initial data analysis and integration of hydrological and social data into one network model. Identification of needs for further data collection.

Phase three: One-month field trip to New Mexico for further data collection.

Phase four: Further data analysis and organization.

Phase five: Final three-month trip to New Mexico to finalize data collection as needed.

Phase six: Completion of data analysis and final draft of the dissertation.

4. Expected Results

The expected results of this study will be a model of the social-hydrological network that the acequias in Taos Valley constitute, and an increased understanding of how the structure of this network relates to its genesis and management as well as its sustainability. The intellectual merit of this project will be to contribute to the study of human-environment interactions broadly, as well as to the specific disciplines that are integrated within it. A major obstacle to the study of human-environment interactions is the development and application of a common theoretical language with which to study both human and environmental systems that allows researchers to analytically relate the properties and interactions of the social world to those of the natural world. Combining the frameworks of complex networks and social-ecological systems and the concept of a collective-action problem offers such a language with which to integrate both natural and social phenomena into one model of a human-environmental system.

Additionally, this project will further develop our understanding of how real networks function by analyzing a network that has both social and hydrological nodes and links, as well our understanding of how the structure and dynamics of social-ecological systems affect the outcomes obtained in those systems. Within the field of complex networks, little work has been done that considers them as joint social-ecological phenomena: work has largely been limited to either social or ecological networks alone. Within the field of social-ecological systems, researchers are still struggling to find a family of concepts or framework that is most useful for considering social and ecological dynamics and their interactions.

The broader impacts of this study will be to help resource users and policymakers better understand why irrigation systems like the acequias in New Mexico function as they do. The research methodology of this study is highly participatory on the part of local users, regional officials and technical professionals. The findings of this project will be shared with those locally and regionally involved, and will be applicable to a large range of similar systems found around the world, from Spain and Latin America to Africa, the Middle East, and to Southeast Asia. These findings will help us understand when and how they have sustained themselves, and what advantages and disadvantages they have in comparison to alternative forms of irrigation management.

5. Figures

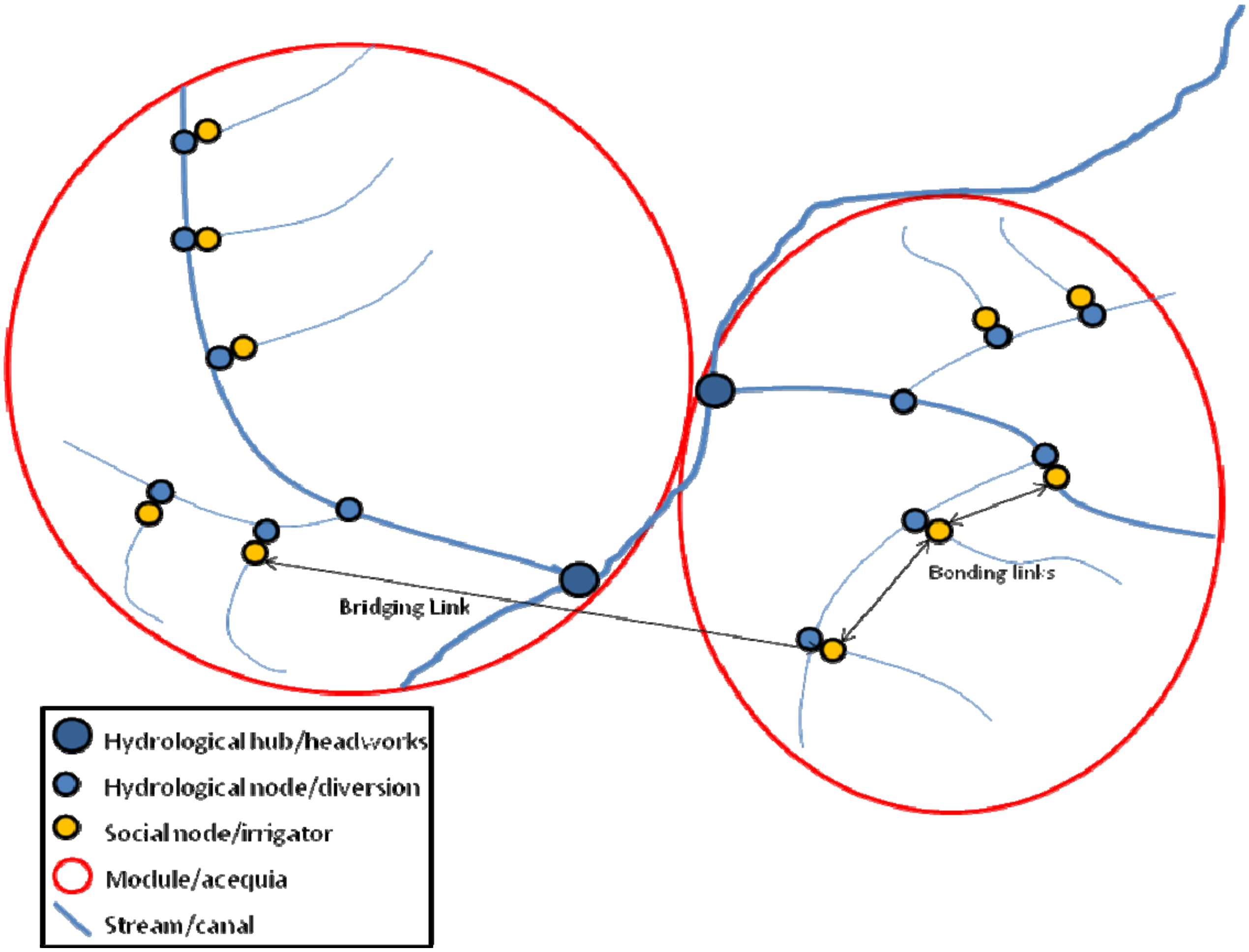

Figure 1: Schematic of a social-hydrological network

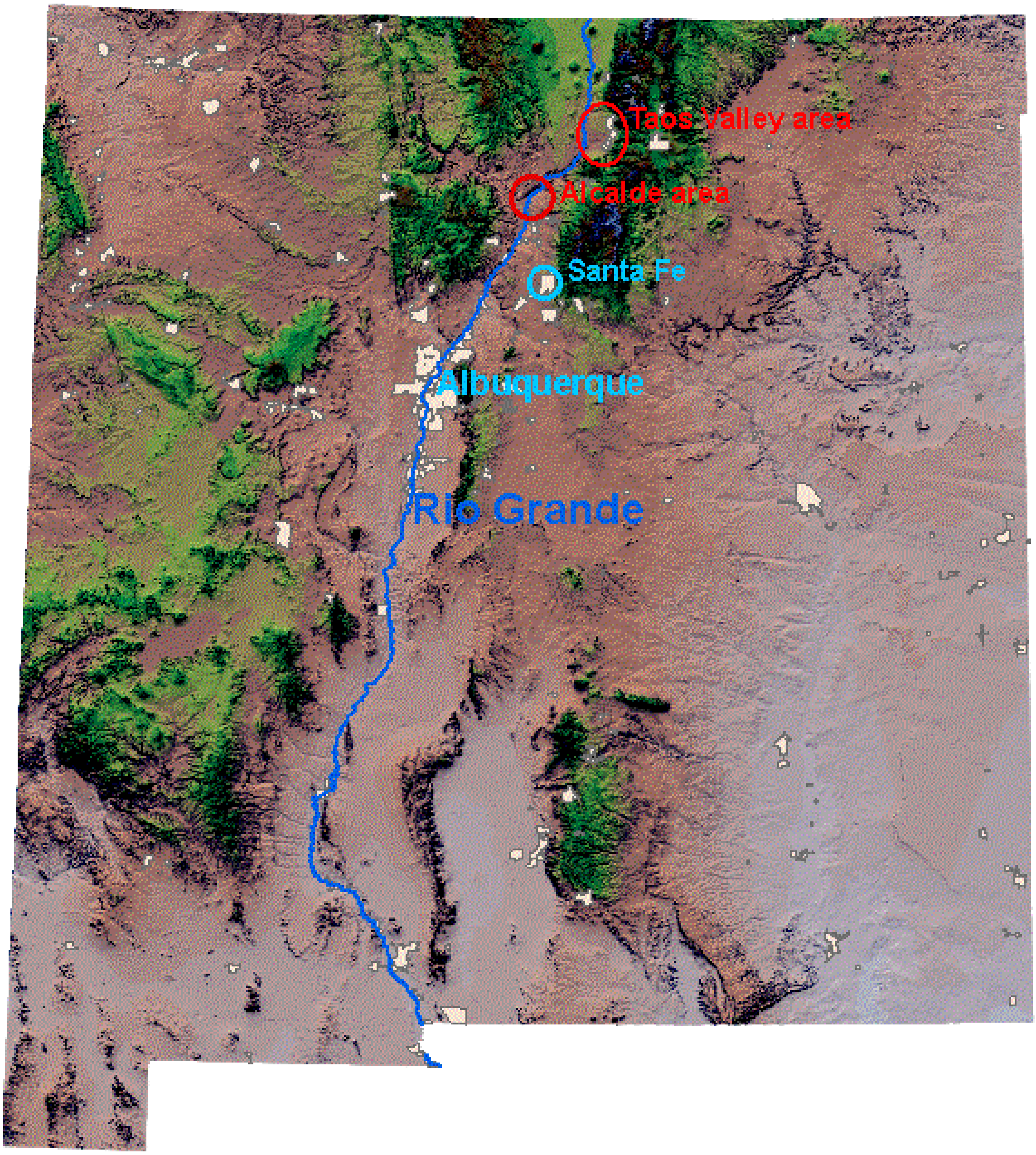

Figure 2: Study Areas in New Mexico

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