EXPLORING THE DYNAMICS OF SOCIAL-ECOLOGICAL SYSTEMS: THE CASE OF THE TAOS VALLEY ACEQUIAS

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This dissertation is dedicated to my father, for his patience.

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This dissertation addresses two primary research questions. First, under what conditions can communities of users sustainably manage natural resources? Second, what types of disturbances are such systems resilient or vulnerable to? To address these questions, this dissertation examines the strengths and vulnerabilities exhibited by communities of irrigating farmers known as acequias in the Taos valley of northern New Mexico. These strengths and vulnerabilities are measured by the acequias' abilities to respond to a range of disturbances, including droughts, urbanization, changing demographics, labor markets, state policies, and water transfers. Several analytical approaches and technologies are used, including longitudinal and spatial statistical analysis, institutional analysis, geographic information systems, and remote sensing. Based on the analysis, we can conclude that the acequias have adopted a particular set of social and biophysical properties that enable successful decentralized responses to droughts over time, but which leave them vulnerable to novel disturbances that result from economic growth and development. One implication of these findings is that such communities will likely experience fundamental disruptions to their identity and traditional functions as they are increasingly integrated into a larger socioeconomic system.

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Chapter One: Introduction and Background

Introduction

Around the world, natural resources are managed in a variety of ways. One basic typology of the governance arrangements applied to such resources divides them into public, private, and common governance regimes. In the past several decades, a research program has developed that examines the conditions under which common property regimes can successfully manage common-pool resources (Baker 2005; Baland and Plateau 1996; Lam 1998; NRC 2002; Ostrom 1990; Schlager et al. 1994; Trawick 2001). More recently, this research program has begun to intersect with another that examines the sustainability of social-ecological systems over time and in the face of a variety of disturbances (Folke et al. 2004; Gunderson and Holling 2002; Walker et al. 2004). Communities managing CPRs are considered to be excellent examples of social-ecological systems.

This dissertation is composed of five chapters that address two basic research questions at the intersection of these two research programs: first, what combination of social and biophysical properties enable community-based natural resource management systems to persist in the face of various disturbances they have faced during their history? Secondly, does this particular combination leave them vulnerable to disturbances that are more recent and novel, and if so, what is the nature of these novel disturbances? Addressing these questions is done by analyzing a set of irrigation communities in northern New Mexico known as acequias.

This introductory chapter explores the family of concepts used in subsequent chapters in more depth and provides a background on the study area where they are applied. Chapter 2 implements a framework for studying the properties of the acequias as a social-ecological system, and explores the properties that have made them robust to droughts over time. Chapter 3 introduces a typology of disturbances to complement the framework used in chapter 2, and further explores the acequias' responses to several disturbances. Chapter 4 conducts an acequia-level analysis to statistically test their robustness or vulnerability to several novel disturbances, as well as the importance of several factors that affect their robustness to droughts. Chapter 5 further explores the effects that these novel disturbances have had on the acequias, and offers some conclusions based on the previous analyses. For a summary of the analysis in each chapter, see table 1.2 at the end of this chapter.

The remainder of this chapter is organized as follows: first, background is given on the acequias in New Mexico. Second, a theoretical discussion is presented on the important concepts that are used throughout subsequent chapters. This is particularly important given the high level of ambiguity, inconsistency, and confusion that is contained in the various literatures that employ these concepts. The aim of the later chapters is to further our knowledge via empirical analysis, but this is only possible if the concepts operationalized have well-understood meanings.

1.1 Background on the acequias and Taos valley

The acequias are one example of a community-based irrigation system, of which there are many around the world. The term community-based signifies that at least some portion or element of the resource system is governed by a common property arrangement. Like most community-based irrigation systems, the acequias employ a mix of common and private property arrangements[1].

For the Spanish settlers of New Mexico who wished to farm, common property was a necessary solution to the problem of insufficient rainwater. No one individual could afford the costs required to build and maintain an irrigation system that could provide enough water to make agriculture viable. Because they had no alternative, participation in a common property regime secured invaluable benefits to all members, creating lasting incentives for collective action so long as most participants continued to contribute resources.

In modern-day New Mexico, an acequia has a well-defined political and social meaning. Socially, an acequia refers to a community of irrigators governed by an executive mayordomo and a set of three commissioners (one chairman, one secretary, and one treasurer). It is also the name for the primary irrigation canal each community employs. Historically, the acequias have served as the primary unit of governance for surface water in New Mexico. They are formally political subdivisions of the state of New Mexico, and they predate its existence as a state.

The acequias in New Mexico and in parts of southern Colorado are the descendants of the original Spanish colonists, who moved north along the Rio Grande from Mexico beginning around 1598. As Rivera (1998, 5) discusses:

> *Acequia technologies and irrigation methods employed by the hispano mexicanos in the new province were melded from diverse sources. Historians agree that these antecedents included the irrigation practices common to the arid regions in the south of Spain, particularly Andalusia and Valencia, based on traditions from the Roman period; the superimposition of Arabic customs and techniques during the seven centuries of occupation of Spain by the Moors; and the influence of Pueblo Indian agriculture as observed by early Spanish explorers and settlement pioneers.*

Rivera (1998) notes the institutional similarities between modern-day acequias and their historical predecessors in Spain. Each acequia has a *mayordomo,* who manages its water and is analogous to the Spanish *cequier* or *partidor de aguas*. The institutional regime of common property ownership was also carried over. One important physical piece of common property is the acequia madre, or the main canal that an acequia uses to transport water. The practice persists in most acequias of holding an annual spring meeting to organize the collective cleaning of its acequia madre. Grazing lands and the water used to irrigate have also been historically common property in the acequias.

Many of the acequias that originally established themselves in New Mexico are no longer in existence, in large part because of developing municipalities and irrigation and conservation districts, which have effectively competed for the limited water supplies. Acequias within the city limits of Albuquerque and Santa Fe, for example, are no longer functioning. In

[1] Common property imposes a set of obligations on each member of the community if they are to continue appropriating from the resource being governed. Private property regimes do not generally impose similar obligations on rights owners.

Albuquerque's case, they have been subsumed into the Middle Rio Grande Conservancy District, which is a large association of irrigating farmers.

The majority of the traditionally functioning acequias in New Mexico are in the northern half of the state, which is more mountainous and therefore receives more water. The study area for this project is in Taos valley in Taos County. Taos County is one of the northern-most counties in New Mexico, sharing a border with Colorado (see figure 1.1). 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 are now facing the threat of economic development, changing demographics, and the penetration of water markets. Many of these pressures are coming as a result of economic growth in the town of Taos, the primary municipality in Taos valley and Taos County.

An additional source of disturbance has been the implementation of state-level policies mandating that the New Mexico Office of the State Engineer (OSE) quantify all water rights and regulate them in accordance with the principle of prior appropriation; a principle which, while underlying the acequias' claims to their historically used water, may also undermine their common property institutional arrangements. This mandate has been implemented in Taos through a formal water rights adjudication suit referred to commonly as the *Abeyta* case (State of New Mexico ex rel. State Engineer v. Abeyta and State of New Mexico ex rel. State Engineer v. Arellano), the purpose of which is to quantify and prioritize all of the individual-level water rights in the valley.

An interesting response of many of the acequias across the state to these novel pressures has been to form associations, such as the Taos Valley Acequia Association, which formed in 1987 as a response to the water rights adjudication. Many of these associations have also become regional members of a state-wide New Mexico Acequia Association. Despite these efforts and some positive outcomes that have resulted, the future of acequias in New Mexico remains uncertain.

Figure 1.2 displays the study area. Taos valley is 2,070 meters above sea level and encompasses roughly 400 square kilometers. The acequia-irrigated area in the valley is around 40 square kilometers. There are approximately 51 to 55 acequias in the valley, although this number depends to some extent on what is considered to be an acequia. The main use of water in the valley is irrigation. 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 between 11 and 13 inches per year. Unfortunately, much of this is quickly lost as run-off.

Figure 1.1: Location of Taos County and Taos valley

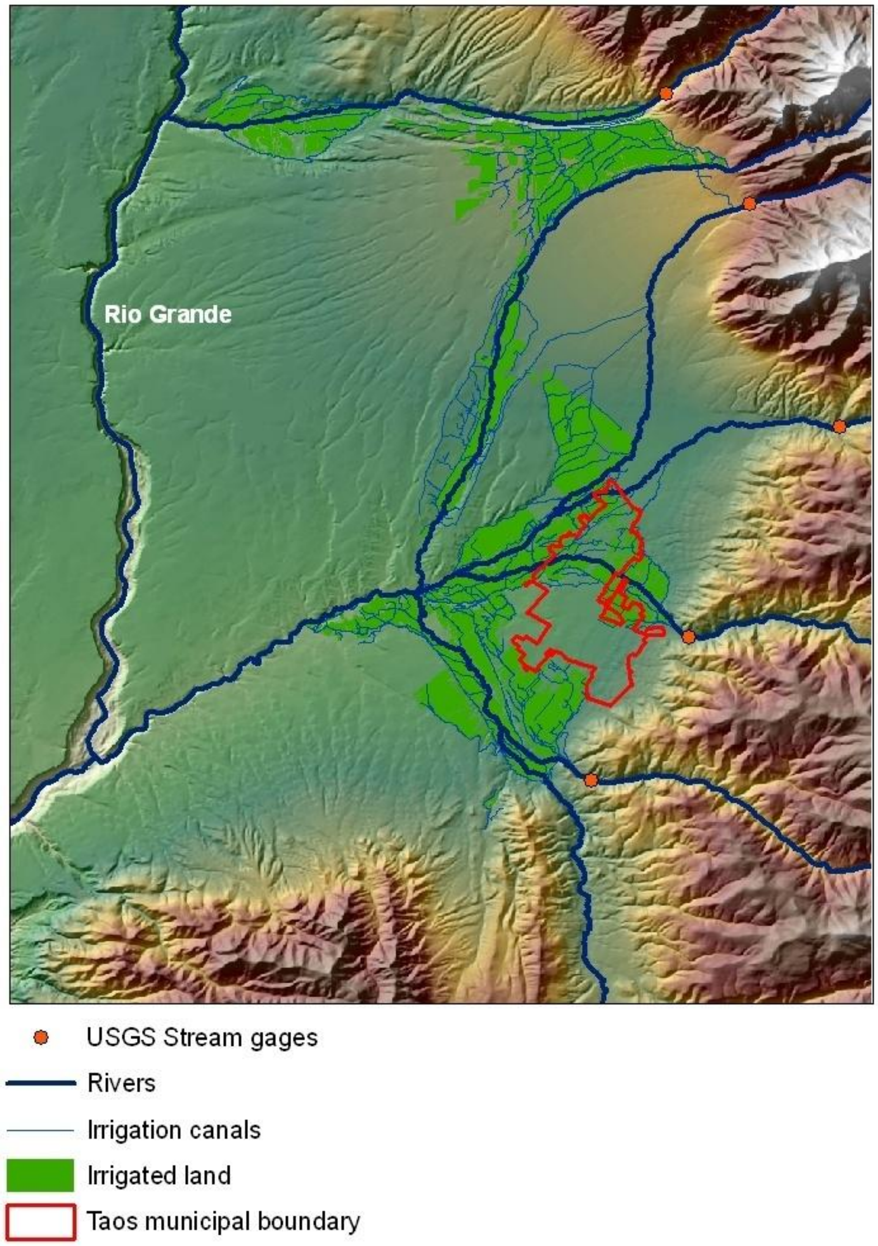

Figure 1.2: Taos valley

1.2 Common-pool resource management

The puzzles to be addressed in this study involve the concept of a collective-action problem. A collective-action problem is a dilemma for a user community caused by a divergence between individual and community-level interests. In these situations, the pursuit of individual gain is collectively harmful, and it can be difficult to organize people to act collectively in pursuit of common interests. In order for a SES involving communities managing common-pool resources (CPRs) to be sustainable, collective action problems must be continually resolved in order to maintain cooperation among the resource users.

A CPR is defined by two characteristics: 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 otherwise impose obligations on those who use it. Examples of CPRs include water, grazing land, forests, and fisheries. Much of the literature on CPR management has focused on determining the combination of conditions that make it possible for communities to successfully maintain the collective action needed to sustain a CPR that is used by their members.

The properties of CPRs, such as irrigation systems, lead to at least two types of collective-action problems: appropriation problems and provision problems (Ostrom et al. 1994). An appropriation problem relates to motivating individuals to forego excessive consumption of a subtractable resource, 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 is a problem of motivating individuals to contribute to the resource system and 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. Solving each of these problems is analogous to internalizing negative and positive externalities, respectively.

In order to effectively manage a CPR, incentives need to be devised that limit appropriation levels and boost provision levels. Providing these incentives is, in turn, a second-order provision problem associated with providing public goods such as monitoring, enforcement, and conflict resolution (Ostrom et al. 1994). As a result of these problems, the management of CPRs is not a simple task. There is substantial documentation of both successes and failures of various CPR management regimes (NRC 1986, 2002).

Overcoming collective-action problems is difficult because participants are uncertain about the future actions of others, and have reasons to expect some degree of self-serving behavior on their part. In terms used by the literature, humans are considered to be self-interested and boundedly rational. Many scholars studying community-based CPR management have focused on the role institutions play in overcoming these difficulties. North (1990a) states that institutions arise in order to reduce the uncertainty in social situations by ordering participants' relationships. By reducing uncertainty, trust and norms of reciprocity may be built and sustained, and collective action may become possible. Institutions are defined by Ostrom (1986, 5; emphasis in original) as “potentially linguistic entities . . . that refer to prescriptions commonly known and used by a set of participants to order repetitive, interdependent relationships” where “prescriptions refer to which actions (or states of the world) are *required, prohibited*, or *permitted*.” Institutions may be seen as a commonly understood code of behavior that potentially reduces uncertainty, mediates self-interest, and facilitates coordinated action.

Institutional arrangements are not costless, however. Their development and implementation impose *transaction costs* on those who produce them as public goods for a community. Transaction costs are “the costs of measuring and enforcing agreements” (North 1990b, 362). If a system develops a set of institutional arrangements that imposes overly burdensome transaction costs on those who implement them, it is likely that it will not persist. As such, a social system in a SES that is faced with a set of social dilemmas imposed by a biophysical system must construct institutional arrangements that sustain collective-action without incurring excessive transaction costs.

1.3 Social-ecological systems, resilience and robustness

Much of the CPR literature is concerned with the sustainability of collective-action over time. Research on social-ecological systems is likewise concerned with the idea of persistence over time, and the concept of sustainability lies behind much of the analysis presented in subsequent chapters. It has become quite popular in the last several decades, particularly since the Brundtland report (UNWCED 1987) introduced a now commonly cited definition of sustainable development: “development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Much of this popularization has resulted from an increasing recognition of the impacts that human beings have on the natural environment (Vitousek et al. 1997) and how dependent they are on it (Daily 1997).

However, the concept of sustainability has proved difficult to implement or operationalize. Instead of sustainability, many scholars have turned to other terms to analyze the ability of systems to persist over time by responding adaptively to disturbances or perturbations. Such terms include adaptive capacity, resilience, robustness, stability, and transformability. These terms are used by various communities of scholars for different purposes, such that a brief review of their meanings can lead to some confusion. At times they are used interchangeably, and other times different authors use a term in contradictory ways.

One community of scholars has attempted to apply these terms to analyze how humans may interact sustainably with their environment, which has led to an interest in applying them to social-ecological systems (SESs). In this dissertation I am primarily concerned with this type of application, and I focus on the concepts of resilience and robustness. As they are central to the analysis in subsequent chapters and subject to some confusion in the literature, it is worthwhile to give an overview of each of them here. Each term has already been the subject of a wealth of analysis and conceptualization ((Abel et al. 2006; Anderies et al. 2004, 2006, 2007; Carlson and Doyle 2002; Carpenter et la. 2001; Carpenter and Cottingham 1997; Folke et al. 2004, 2005; Holling 1973; Janssen et al. 2007; Walker et al. 2002, 2004, 2009). What has not been done is a systematic comparison of how each relates to the other with respect to their application to SESs.

This chapter begins this comparison, with the view that the two concepts are ultimately complementary and slightly overlapping.

In broad terms, the difference between resilience and robustness may not be that large. Each generally regards the ability of a system to maintain important functions and relationships in the face of a disturbance. One difference is that scholars studying SESs have used resilience much more than robustness to organize their work. Keyword searches conducted on October 30, 2009 for resilience and robustness in the journal *Ecology and Society*, a primary scholarly forum for the study of SESs, returned 133 hits and six hits, respectively.

1.4 Social-ecological systems

The usefulness of robustness and resilience is a function of the kinds of systems to which we might apply them. We are interested in the robustness and resilience of complex adaptive systems, as opposed to relatively simple, non-hierarchical systems. Moreover, in studying the possible sustainability of human-environment interactions, we are interested in a particular kind of complex adaptive system: a social-ecological system (Gallopin et al. 2001).

SESs are defined by Anderies et al. (2004) as social systems "in which some of the interdependent relationships among humans are mediated through interactions with biophysical and non-human biological units." In SESs where CPRs are managed, an important component of these interactions is the positive and negative externalities that users create by either consuming a resource or providing resource infrastructure and other public goods.

In order to study the robustness or resilience of a SES, we have to be able to observe their dynamics over time. Several frameworks that have been proposed for studying SESs and their over-time dynamics, including Gunderson and Holling's (2002) Panarchy concept, Ostrom's (2007) diagnostic framework, Anderies et al.'s (2004) approach, Janssen et al.'s network approach (2006), and the robust control framework presented by Anderies et al. (2007).

Ostrom's (2007) framework, which is the one adopted in chapter 2, attempts to reflect the hierarchical qualities of complex social-ecological systems. She presents a tiered framework, where components of a SES are in turn decomposable into multiple subcomponents or properties, to be used as needed by the analyst. There are six primary components of a SES in this framework: (1) A resource system, (2) Resource units, (3) Users, and (4) A governance system, (5) external social, economic, and political settings, and (6) related ecosystems. These interact to produce important outcomes, and are shown in figure 1.3. Figure 1.4 displays a decomposition of each of the six primary components. 3^{rd} and 4^{th} level variables are also possible.

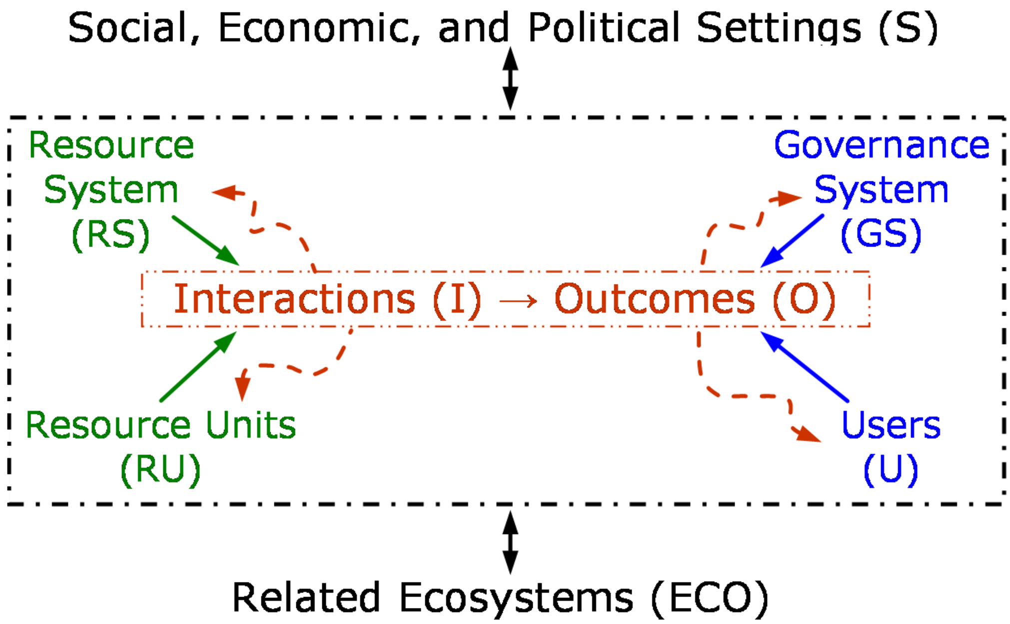

Figure 1.3: Framework Level one (source: Ostrom 2007, 15182)

Social, Economic, and Political Settings (S)

S1- Economic development. S2- Demographic trends. S3- Political stability.

S4- Government settlement policies. S5- Market incentives. S6- Media organization.

Resource System (RS)	Governance System (GS)
RS1- Sector (e.g., water, forests, pasture, fish)	GS1- Government organizations
RS2- Clarity of system boundaries	GS2- Non-government organizations
RS3- Size of resource system	GS3- Network structure
RS4- Human-constructed facilities	GS4- Property-rights systems
RS5- Productivity of system	GS5- Operational rules
RS6- Equilibrium properties	GS6- Collective-choice rules
RS7- Predictability of system dynamics	GS7- Constitutional rules
RS8- Storage characteristics	GS8- Monitoring & sanctioning processes
RS9- Location	
Resource Units (RU)	**Users (U)**
RU1- Resource unit mobility	U1- Number of users
RU2- Growth or replacement rate	U2- Socioeconomic attributes of users
RU3- Interaction among resource units	U3- History of use
RU4- Economic value	U4- Location
RU5- Size	U5- Leadership/entrepreneurship
RU6- Distinctive markings	U6- Norms/social capital
RU7- Spatial & temporal distribution	U7- Knowledge of SES/mental models
	U8- Dependence on resource
	U9- Technology used
Interactions (I) →	**Outcomes (O)**
I1- Harvesting levels of diverse users	O1- Social performance measures (e.g., efficiency, equity, accountability)
I2- Information sharing among users	O2- Ecological performance measures (e.g., overharvested, resilience, diversity)
I3- Deliberation processes	O3- Externalities to other SESs
I4- Conflicts among users	
I5- Investment activities	
I6- Lobbying activities	

Related Ecosystems (ECO)

ECO1- Climate patterns. ECO2- Pollution patterns. ECO3- Flows into and out of focal SES.

Figure 1.4: Level 2 components and properties (source: Ostrom 2007, 15183)

1.5 Resilience

The analytical use of resilience began in ecology, mainly within ecological stability theory and Holling's (1973, 14) definition of resilience as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables." Within ecology there has been a high level of conceptual confusion regarding resilience and related terms (Grimm and Wissel 1997).

One primary difference between resilience and robustness is the strong connection between resilience and other concepts such as *attractors, states, steady states, stability domains, domains of attraction, basins of attraction, regimes,* and *equilibria*, none of which are referenced frequently by literature on system robustness. The concept of a system *state* is a fundamental as any associated with resilience. Walker et al. (2002, 5) describe the *state* of a system in the following way:

> *The 'state' of a system at a particular instant in time is the collection of values of the state variables at that time…In complex systems whose description requires many state variables, the term 'state' is loosely used to describe a characteristic of the system, rather than its state. For example, the lake is in a eutrophic 'state', or the rangeland is in a shrub-dominated 'state.' Such a loose definition is acceptable in everyday situations, but not when we want to analyze a system more carefully.*

What we commonly refer to as a system "state", (ex. a lake being eutrophic), actually represents a whole collection of states, or a particular set of state variable values. A state variable is simply a variable whose values help to characterize the present state of the system at a particular period of time. In a dynamical system, the evolution of each state variable is described via a differential or difference equation, and the equation for one variable frequently contains other state variables. It was this approach to systems analysis—formalization through differential equations—that originally led scholars to observe the theoretical possibility of multiple equilibria (or *attractors* in mathematical terms, also referred to as steady states) in complex systems (Holling 1973; Lorenz 1963; May 1977). The set of states that leads to this attractor is referred to as a *basin of attraction* (or *domain of attraction*).

A primary motivation for studying the ecological resilience of systems is that they contain multiple basins of attraction within their *phase space* (or state space) which is the set of all possible values of their state variables. A phase/state space has a dimension for every state variable of the system. "For example, if a rangeland system is defined by the amounts of grass, shrubs and livestock, then the state space is the three-dimensional space of all possible combinations of the amounts of these three variables" (Resilience Alliance 2009). Likewise, any particular state that the system occupies has a dimension for every state variable. A basin of attraction is a set of such states that the system tends not to leave once it is in any one of them. If there is only one basin, then the set of states in the basin equals the set of states in the system's phase space. The boundary between two basins of attraction is known as a *threshold*.

A *stability landscape* combines the concepts of thresholds and basins of attraction, and is defined as "the various basins that a system may occupy, and the boundaries that separate them" (Walker et al. 2004). Figure 1.5 depicts a stability landscape that employs a ball-and-cup metaphor, which can be used to illustrate two distinct conceptualizations of resilience that have been used. Here, the system is defined by two state variables (x axis, y axis) that specify the location of a ball as it moves within or between the depressions in the stability landscape.

There are two definitions of resilience, based on whether or not a single or multiple basins of attraction are assumed to be present in a system's stability landscape. One definition of resilience is the period of time it takes in order for a system to return to an equilibrium state after a disturbance. This has been called *engineering resilience*. In his original work, Holling (1973, 14) labeled this concept stability, stating that it "represents the ability of a system to return to an equilibrium state after a temporary disturbance; the more rapidly it returns and the less it fluctuates, the more stable it would be."

In figure 1.5, engineering resilience would be defined by the slope of the basin of attraction where the ball is located. This definition presumes a single global equilibrium for the system that is associated with its critical functions. Since no alternative steady states are possible, we are primarily concerned with how long it may take for the system to return to equilibrium after a disturbance, and the entire objective of the system is to maintain these functions and this equilibrium state.

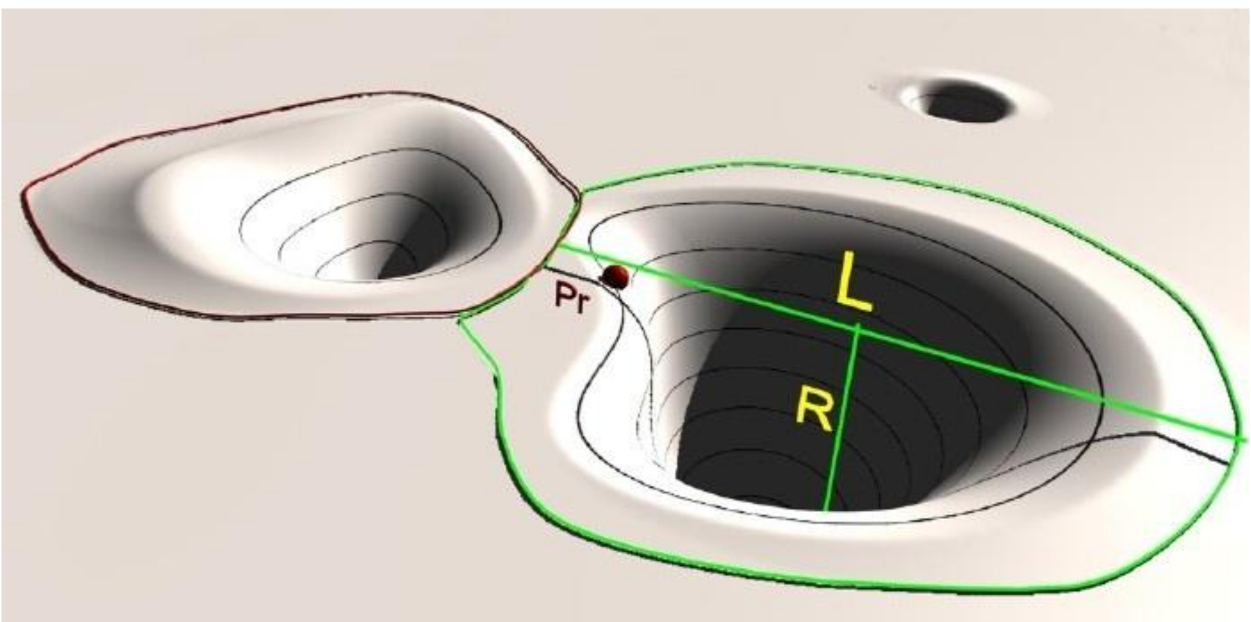

Figure 1.5: A 3-dimension stability landscape. Adapted from Walker et al. (2004).

The alternative definition of resilience is known as *ecological resilience*. Under this conceptualization, multiple equilibria within multiple basins of attraction are presumed to exist, which figure 1.5 illustrates. Here, there are three aspects of resilience, R (Resistance) L (Latitude) and Pr (precariousness). Walker et al. (2004) define these in the following ways[2]:

Latitude: the maximum amount a system can be changed before losing its ability to recover

Resistance: the ease or difficulty of changing the system; how 'resistant' it is to being changed

Precariousness: how close the current state of the system is to a limit or 'threshold'

Figure 1.5 illustrates several other important ideas related to resilience. First, there are in fact two ways for a system to switch into an alternate basin of attraction: first, the system state can move beyond a threshold along a particular dimension, and second, the stability landscape can change, shrinking a basin of attraction so that the normal fluctuations of the system's state will move it beyond the threshold. Figure 1.6 demonstrates these two possibilities. Likewise, there are two ways of maintaining a system within a basin of attraction: first, by minimizing variation in system states (increasing stability or resistance), and second, by widening the basin of attraction (increasing latitude) so that more variance can be tolerated without crossing a threshold. However, these two methods may not be complementary.

In addition to illustrating shifts in basins, figure 1.5 illustrates the condition of hysteresis, where a set of state variables values that define the threshold between basins changes after a system has moved from one basin to another. When this happens, returning a particular state variable to a previous value may not be enough to return the system to a previous basin of attraction associated with that value. This makes reversing the effects of a basin change potentially very difficult. Beisner et al. (2003) argue that it is only the parameter shift disturbance (change in the stability landscape) that technically exhibits hysteresis, while the state variable shift exhibits an analogous but distinct phenomenon of low reversibility. In either case, it is more difficult to re-enter a basin of attraction after leaving it.

There are several limitations to the depiction of a SES by a stability landscape in figure 1.5. First, it does not allow us to consider the dynamics that occur between the movement and variability of a system's state variables and its stability landscape, both of which are part of its definition. It is likely that there are important causal relationships between these two, with one hypothesis being that the normal fluctuations of state variables help to maintain the latitude of the basin along each of their respective dimensions. Holling (1973), for example, makes the interesting argument that in some cases, such as the Spruce Budworm system, low stability or resistance due to high fluctuations in system states can produce high resilience. Holling (1995) describes several examples of a pathological type of natural resource management that focuses on minimizing the variability of a target state variable, and in so doing lowers the resilience of the ecosystem containing that variable. Another problem with figure 1.5 is that it does not illustrate the relative speeds at which different state variables change their values. This is likely important, and Wilson (2002) argues that management systems should be geared more towards

[2] One feasible interpretation of these terms could be that Latitude is the magnitude deviation of a disturbance that is required in order to flip a system into an alternative state. Resistance is the buffering capacity of the system to this deviation. The ultimate effect on the system, or how much the system is moved, = L – R. In an irrigation system, L could be a deviation in streamflow and R could be the storage capacity of the system.

stabilizing the relatively slow-moving variables, as these are more fundamental to the long-term sustainability of the system.

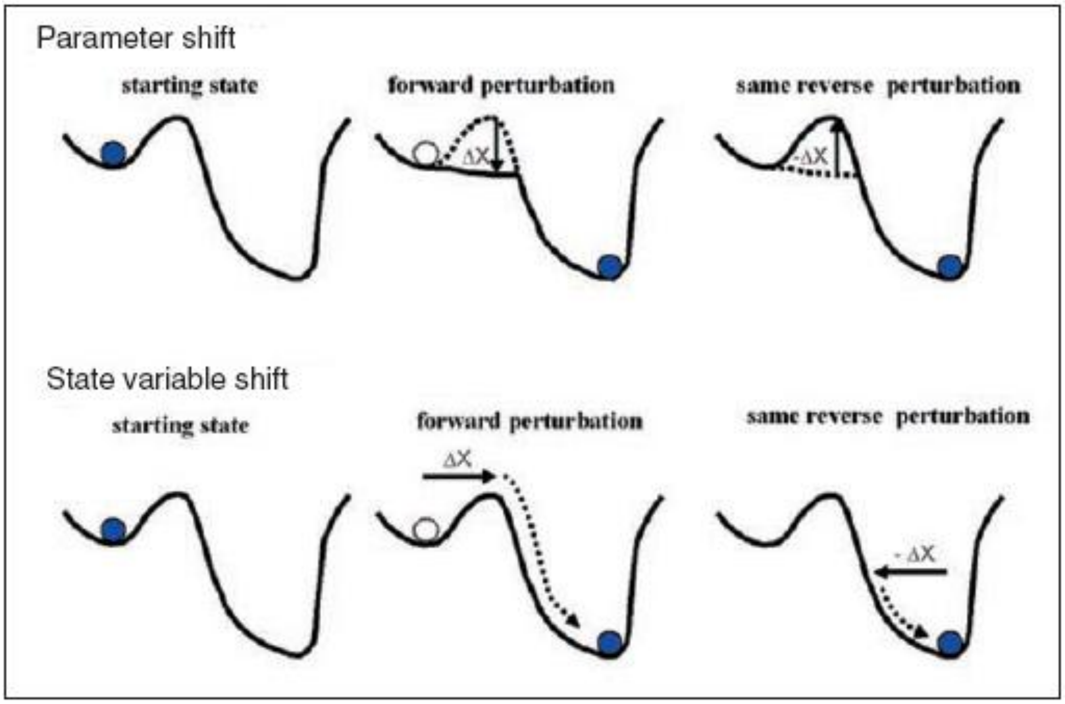

Figure 1.6: Two types of disturbances: changes in parameters vs. state variables (Source: Beisner et al. 2003, 381).

Additionally, figure 1.5 gives an impression that resilience is a quantitative value pertaining to a particular system, almost as if it were another state variable. This seems impractical. The most likely candidate for operationalizing resilience in this way from figure 1.5 is probably *latitude*, which would be the size of the basin of attraction along its various dimensions. This approach has some complications. First, if we define resilience by the *latitude* (or resistance, for that matter) then there are as many dimensions of resilience as the system has state variables, and so resilience cannot be treated like a state variable itself.

Another complication of this approach is that as the values of resilience of a system along its dimensions are interdependent. Figure 1.5 in fact subtly indicates this, because the shape of the basin is not a square or rectangle, which would imply independence (moving the system's state along one dimension does not move it any closer to or further from a threshold along another dimension). In a basin of attraction where the resilience along one dimension is a function of other state variables, we can actually increase resilience along this dimension by moving these other variables without necessarily affecting the system along the original dimension. So, it is not the overall size or latitude alone that affects resilience along a particular dimension, but the *shape* of the basin, or the extent to which the resilience along one dimension is affected by the values of other state variables. Not only is resilience specific to a particular dimension, but it specific to a particular point along this dimension.

Empirical analyses have not tended to quantify resilience in such a precise way, and Walker et al. (2004) recognize the difficulties in formalizing the concepts with respect to SESs. Likewise, formalizations of complex systems via differential equations have been used primarily to prove the theoretical possibility of system behaviors, rather than as empirical tests of hypotheses regarding this behavior. Instead of such formalization, resilience analyses of ecological systems have involved specifying a system's variables and qualitatively describing their relationships with each other as being self-reinforcing and creating one or more basins of attraction (Carpenter and Cottingham 1997; Folke et al. 2004; Scheffer et al. 2001; Walker and Salt 2006).

The state variables included in these analyses frequently include the population of various species or functional groups, a particular environmental parameter such as pH or turbidity, or a physical stock or flow, such as a chemical concentration, nutrient flux or stream flow. One empirical example involves vegetation in semi-arid regions that maintains itself by affecting soil structure. Scheffer et al. (2001, 594) describe two possible basins: "Perennial vegetation allows precipitation to be absorbed by the topsoil and to become available for uptake by plants. When vegetation cover is lost, runoff increases, and water entering the soil quickly disappears to deeper layers where it cannot be reached by most plants." The plants' presence makes the environment more amenable to plant growth; without this, producing vegetation in a desertified area becomes much more difficult. Similarly, Laycock (1991, 429) describes how, once overgrazing has removed native vegetation from an area, lowering the number of grazing animals to earlier levels frequently does not return the original basin and its associated vegetation. He states: "It has long been recognized that shrubby invaders of desert grasslands are slow to relinquish dominance once they become established because of fire suppression, heavy grazing or other factors." Many areas in New Mexico exhibit this precise characteristic following extensive overgrazing.

Unfortunately, similar case-based applications to SESs are not abundant in the literature, leading some scholars to question the applicability of resilience to SESs in lieu of robustness (Anderies et al. 2004). However, there have been some empirical applications of resilience to SESs, employing both social and biophysical data (see Gonzalez et al. 2008; Walker et al. 2009).

One question that needs to be answered to apply resilience to a SES is, what would a basin of attraction look like in a social system, or in a SES that has social components? An alternative way of asking this is, what are the relevant state variables in a social system that interact to produce a self-reinforcing set of relationships?

One relevant place where multiple equilibria in social situations have been found is in game theory of repeated situations. In the game experiments conducted in this research participants are commonly presented with two basic choices, to cooperate or to defect. Cooperation depends to a large extent on whether or not the relevant population has individuals who behave like conditional cooperators (Ostrom 2005). Conditional cooperators tend to be highly reciprocal in their decisions, cooperating with cooperators and defecting when others defect. The pay-off matrix shown on table 1.1 characterizes what a conditional cooperator would face in a two-person game. The numbers in the matrix indicate the pay-off, and the letter corresponds to the player who receives that pay-off. Whatever Player B does, player A's best strategy is to do the same.

		player A	
		cooperate	defect
player B	cooperate	5A, 5B	4A, 0B
	defect	0A, 4B	2A ,2B

Table 1.1: Pay-offs of a conditional cooperator

The extent to which a social setting can exhibit alternative self-reinforcing equilibria is likely a function of the extent of conditional cooperation (reciprocity) that occurs. If two participants each cooperate on the condition that their partner does, then one of two equilibria can occur: each cooperates, or neither cooperates. If reciprocity is strong, then the important factor becomes trust, or the extent to which a participant actually believes she is interacting with another conditional cooperator. The ability of someone to build a reputation and be identifiable as such depends in turn on several features of the community and their institutions that have been identified in the CPR literature as favoring sustained collective action, such as small-to-medium group size, effectively preventing outsiders from accessing the resource, and certain types of homogeneity.

Camerer (2003, 12) describes two basins of attraction that occur in a set of game theory experiments, or what he refers to as "path-dependent coordination in 'continental-divide' games." The pay-off structure for each player in these games is analogous to table 1.1. Each player chooses a number between 0 and 14, and their payoff matrix yields the highest payoffs when the number they choose is close to the median number chosen by all the other players. This is a coordination game with two Nash equilibria, and it does produce self-reinforcing behavior that leads to two basins of attraction in a system with one state variable defined by the median level of coordination exhibited by the players. This is shown in figure 1.7, where the x-axis is the period, or round, and the median is the median number chosen by each of the players which defines the state of the system. "The game is called the continental divide game because medians below 7 are a 'basin of attraction' (in evolutionary game theory terms) for convergence toward the equilibrium at 3. Medians above 8 are a basin of attraction for convergence toward 12" (*ibid*, 14). An interesting question then is to what extent do the payoffs participants receive in real-world CPR situations resemble a coordination game vs. a cooperation game? Or, similarly, do most participants in CPR settings behave like conditional cooperators?

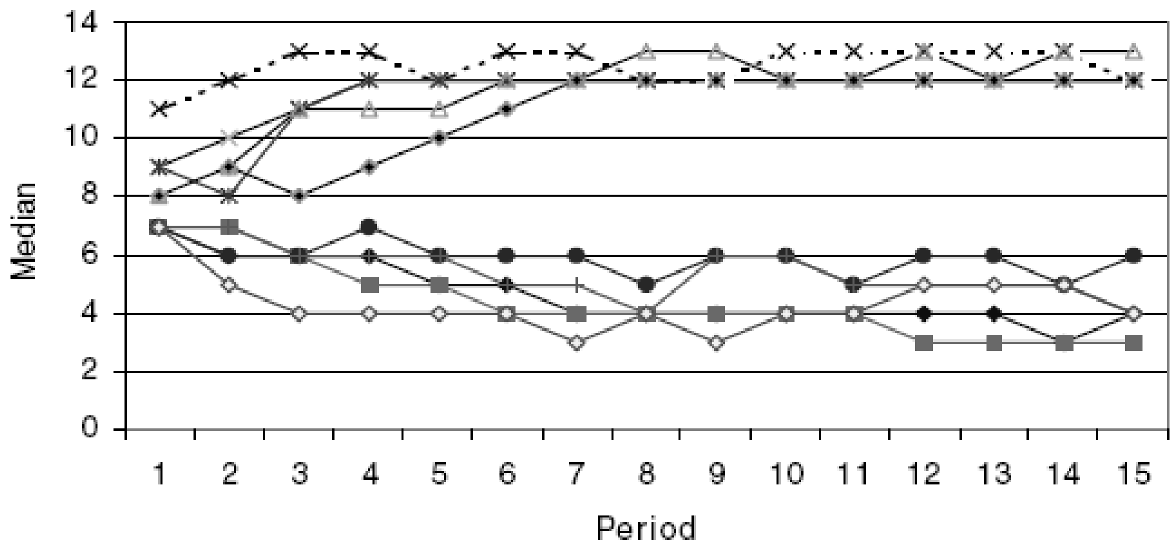

Figure 1.7: Multiple basins of attraction in a series of game theory experiments (Source: Camerer 2003, 15).

To sum up, a common element in ecological basins of attraction and the behavior exhibited by a set of conditional cooperators here is that each situation exhibits self-reinforcing behavior. It is this self-reinforcement that can make it difficult to switch from one basin to another. I would argue that both real-world social and ecological systems exhibit this self-reinforcing behavior. The challenge now becomes applying both to an integrated analysis of a social-ecological system. This is attempted in chapter 2.

1.6 Robustness

Robustness may be 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). While there are various uses of the term robustness, it seems that most everyone agrees that it regards the persistence of a particular *feature* of a system with respect to a particular *disturbance*. "Speaking of the robustness of a system only makes sense after having defined those features whose persistence is under threat" (Lesne 2008, 511). This is similar to the point made earlier regarding resilience: that a system's resilience is always relative to a particular dimension, and to whatever disturbances that might move it along that dimension.

A review of the literature that has used the term robustness quickly reveals a distinct scientific lineage from resilience. Jen (2003, 14) distinguishes between two types of robustness as they have been used in the literature: 1) robustness of system function with respect to alterations in its structure, and 2) robustness as the ability of a system to switch between "multiple strategic options" without a change in structure.

Interest in robustness to structural change is motivated by the observation that important functions result from certain structures or architectures within a system, and that some structures are comparatively better able to preserve these functions as they experience a loss or shift in components. This subject has been actively researched by scholars interested in the robustness of networks to node or link failures (Barabasi 2002; Dunne et al. 2002, 2004) This literature often uses the concepts of resilience and robustness interchangeably (Newman 2003). Lacking a dynamic component, much of this literature does not involve analyzing a response of the system to the disturbance it experiences.

An interesting question here is, what is the relationship between a system's *structure*, as it relates to robustness, and its present basin of attraction? The two seem like very similar concepts. If they are interpreted to be closely related or identical, then the question we end up asking of a system with respect to this type of robustness is, can it maintain a particular function even if it switches into an alternative basin of attraction?[3]

Jen compares the second definition, the ability to respond strategically, to phenotypic plasticity, defined as "the ability of a single genotype to produce more than one alternative form of morphology, physiological state, and/or behavior in response to environmental conditions" (West-Eberhard 1989, 249)[4]. Here, a comparison that Ostrom (1999, 524) makes between genotypes and institutions is relevant. "Self-organizing resource governance systems have two structures that are somewhat parallel in their function to the concepts of a genotype and a phenotype in biology. . . The genotypic structure characterizes the set of instructions encoded in DNA to produce an organism with a particular phenotypic structure. A rule configuration is a set of instructions on how to produce the structure of relationships among individuals in an action situation that is also affected by the biophysical world and the kind of community or culture in which an action situation is located."

What I will call institutional robustness then is analogous to phenotypic plasticity, and we are able to ask, in a social context, to what extent does the set of instructions contained within a set of institutions enable a group of participants to change their strategies in order to maintain a particular feature of their system in the face of environmental fluctuations or disturbances? It is important to note that the genotype or the institutional arrangements are each more fundamental to the identity of a system than are its phenotype or strategies, as the latter are interpreted as transient manifestations of the former, cued by changes in a system's environment.

This implies that adaptations can occur at the level of the genotype or the phenotype. In a SES, this is analogous to institutional change versus implementing certain strategies based on those institutions. The analogy may break down if we ask whether institutional arrangements can be subject to natural selection in the same way that genotypes may be, but it is an interesting question. An additional layer of complexity is added if we recognize that institutional arrangements may be changed in accordance with other arrangements. One way of differentiating levels of institutional arrangements in this way is to consider operational-level,

[3]A very promising example of how a system's structure and its basin of attraction could be closely related is a food web. Food webs have been both the focus of network analyses among network theorists and of stability analysis in community ecology.

[4]Surprisingly, De Visser et al. (2003) state that "robustness is the invariance of phenotypes in the face of perturbation", which seems to be directly contradictory to the previous definition. However, De Visser et al. are primarily concerned with *genetic robustness*, which is actually the first type of robustness discussed earlier: the robustness of a function with respect to a change in its structure; in this case, it is the robustness of the function of a genotype (to produce a phenotype) to genetic mutations that is under consideration. This example illustrates how much care is required in order to use the concept of robustness and related concepts usefully and meaningfully.

collective-choice level, and constitutional-level institutions, where each successive level specifies the conditions under which and how institutions at the preceding level are to be altered (Ostrom 2005). At the most transient level, operational rules specify what coordinated actions participants are to make under particular circumstances.

We now want to ask whether there is a correlate from the literature on resilience to this notion of institutional robustness as the availability of strategic options. The most likely candidate has not yet been discussed, but is commonly seen in the resilience literature: adaptive capacity. This concept, also referred to as adaptability, comes primarily from evolutionary biology and has sometimes been used interchangeably with resilience. Similar to resilience and robustness, it is used by different authors in different ways (Gunderson 2000; Carpenter et al. 2001; Folke 2006). Walker et al. (2004) discuss the concept as I intend to use it here:

> *In a SES, adaptability is the capacity of actors in a system to influence resilience. In a SES, this amounts to the capacity of humans to manage resilience….because human actions dominate in SESs, adaptability of the system is mainly a function of the social component—the individuals and groups acting to manage the system…their collective capacity to manage resilience, intentionally, determines whether they can successfully avoid crossing into an undesirable system regime, or succeed in crossing back into a desirable one.*

They continue by describing the ways in which humans can manage resilience based on the components of resilience in figure 1.5. I include here a slightly different version of the list they provide:

1) Humans may change the value of a particular state variable to move the system away from a threshold along a particular dimension (not necessarily the same dimension as the state variable that is altered).

2) Humans may change the shape of the stability landscape.

Keeping with the definition of robustness as the latitude a system has along a particular dimension in a basin of attraction, we can define institutional robustness and adaptive capacity as the ability of the human managers of the system to affect the system's state variables or the shape of the basin (the stability landscape) along these various dimensions. Provided that a primary system function is to maintain a particular state variable within a range of values, this appropriately defines institutional robustness as the ability of humans to maintain a particular system function via their institutional arrangements. For example, in a grazing system, one important state variable is the level of livestock/grazing intensity. The system's institutional robustness/adaptive capacity may be increased if the human users have tight control over the population of livestock[5]. This type of robustness need not be limited to humans' control or biophysical variables either: we might ask whether or not they are able to maintain levels of coordination or collective action as a social state variable in the face of a disturbance.

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[5] This emphasis on control is an important component of the application of robustness within the *robust control framework* (Anderies et al. 2007).

Institutional robustness as adaptive capacity is then a result of the strategic options available to a community, which are in turn enabled by its institutional arrangements, in the same way that phenotypic plasticity is enabled by a genotype. This may seem to conflict with a discussion in Janssen et al. (2007) where the authors stipulate adaptation as the process by which institutional arrangements evolve to fit a particular environmental setting and its characteristic set of fluctuations, in the same way as organisms evolve over time to fit a particular environment. From this perspective, institutional arrangements are the result of a process of adaptation, not the source of social adaptive capacity. How can we reconcile these two points of view?

Consider a particular organism whose genotype has evolved to be highly adapted to a particular environment. A critical component of this adaptation is the development of a high level of *phenotypic plasticity*, or the ability to react strategically based on environmental variability. I have likened this phenotypic plasticity to institutional robustness. This type of robustness, which I identified as adaptive capacity, results from a set of institutional arrangements, identified by Ostrom (1999) as the social analog of a genotype. One important way we identify whether an organism's genotype or a set of institutional arrangements are well adapted to an environment is if they enable strategic responses to fluctuations that are common to that environment. In both cases, an important feature of long-term adaptation is the ability to adapt to shorter-term environmental fluctuations. So, we can say that a social system has well adapted institutional arrangements, in the sense that Janssen et al. (2007) mean it, if these institutional arrangements provide them with the strategic options they need to adapt to environmental fluctuations and disturbances they may periodically face.

To summarize, there are two types of robustness: robustness to change in structure, and robustness via strategic options that preserve this structure. The first kind of robustness may be likened to the ability of a system to maintain an important function or feature when it changes from one basin of attraction to another. The second type, institutional robustness, is considered to be analogous to adaptive capacity in a SES, which is enabled by institutional arrangements and allows the social system to manage the system's state variables and stability landscape in order to maintain the system in a particular basin of attraction. In a system where one or more state variables are important system functions, this amounts to maintaining a particular system function, which is the basic definition of robustness.

1.7 Conclusion: Applying resilience and robustness to SESs where CPRs are managed

Ultimately, both resilience and robustness are useful in analyzing the sustainability of complex SESs. The implicit argument put forth in this introduction is that the two are in fact complementary to each other. Each of the concepts cues us to ask particular questions. These questions include:

Resilience

1) What are the relevant components or state variables that characterize the system?

In a SES where a CPR is managed, this likely includes social variables that related to the maintenance of collective action or a related term (social capital, trust, coordination).

2) What are the relationships between these variables? Are they positive or negative, linear or non-linear?

These questions lead us to ask how the state variables may reinforce each other towards particular values or ranges. In a SES, it implicitly asks what factors in the system sustain or discourage collective action.

3) How do these relationships maintain the system within a particular basin of attraction?

This question is an extension of question two, and answering it requires us to make explicit how the relationships between the state variables lead each of them to stay within a certain range.

Robustness:

1) What critical functions does the system perform?

It is possible that a SES performs both biophysical and social functions. These likely include a particular population variable associated with the resource system which may be measured over time, enabling longitudinal analysis.

2) What strategic options are available to the system to aid its response to disturbances? What properties of the system enable these options?

In a SES, this question addresses the institutional arrangements that participants have devised in order to manage the resource system.

Resilience and robustness

1) What relationships exist between a particular basin of attraction or structure and a critical system function? Are there alternative basins or structures that can also produce this function?

This question has implications for the measurement of resilience and robustness. It is likely very difficult to actually empirically measure a basin of attraction at various points in time. It is probably much more feasible in most situations to measure a particular function or state variable, such as biomass or a population of a particular species. If there is a close relationship between this function or state variable and a particular basin of attraction, then we can infer the persistence of that basin of attraction by the persistence of the function. Thus, we may be able to measure both resilience and robustness by measuring one or several state variables over time.

The following chapters will use the acequia irrigation systems in Taos valley, NM, as a way to explore these questions and concepts. To conclude, table 1.2 outlines the disturbances analyzed in chapters 2, 3, 4, and 5, and summarizes the relevant concept, how it is operationalized, and what the observed outcome is. Table 1.2 illustrates several important themes: first, two levels of analysis are used, one at the level of the entire system, and the other at the acequia level. This is particularly appropriate given the multi-level nature of SESs. Statistical analysis occurs at both levels, longitudinally for the whole system in chapters 2 and 5, using a dependent variable that is aggregated across all the acequias, and across acequias in chapter 4, although this too has an element of over-time analysis, because the dependent variable is an over-time average of agricultural production in each of the acequias.

This point highlights a second theme that is important in this study: over-time analysis. Sustainability, resilience, robustness, and related concepts each exhibit themselves over time. As such, time series data are extensively used in this dissertation. A third important theme in this work is the use of multiple methodologies in order to conduct over-time analysis. Analyzing the acequias over time would not have been possible without extensive use of geographic information systems and remote sensing technologies. Finally, table 1.2 indicates that resilience and robustness can be applied to the same system and complement each other, and that the robustness or resilience of a particular system is specific to a particular level in that system and to a particular type of disturbance.

Chapter	Unit	Disturbance	Concept	Metric	Outome
Two	Entire system	Drought	Robustness	Agricultural production measured through NDVI over time	Robust
Three	Entire system	Four types of disturbances as outlined in typology	Robustness or resilience	Maintenance of a basin of attraction, and key features associated with it	Robust, but fragile
Four	Acequias	Drought	Robustness	Agricultural production measured through NDVI across acequias	Robust
Four	Acequias	Urbanization	Robustness	Agricultural production measured through NDVI across acequias	Vulnerable
Four	Acequias	Land fragmentation	Robustness	Agricultural production measured through NDVI across acequias	Vulnerable
Five	Entire system	State-initiated water rights adjudication	Robustness or resilience	Settlement outcome of the court case	Robust or resilient
Five	Entire system	Several that interact: lower resource dependence, economic development, and water transfers	Resilience	Maintenance of a basin of attraction	Vulnerable

Table 1.2: Summary of disturbances studied in chapters 2, 3, 4, and 5.

Chapter 2: Exploring the Acequias' Historical Robustness to Droughts

Michael Cox

Introduction

This chapter measures and explains the historical robustness of the acequias to the droughts they have historically experienced. This is separate from a later analysis in chapter 5, which will explore the incidence of novel disturbances upon them. An important result of these novel disturbances has been a fundamental alteration of the historical basin of attraction that is explored here.

To explore the acequias' response to droughts, this chapter applies a framework (Ostrom 2007) for studying social-ecological systems (SES) to the acequias in Taos valley. There are six primary components of a SES in this framework: (1) Resource units, (2) A resource system, (3) A governance system, (4) Users, (5) external social, economic, and political settings, and (6) related ecosystems. The framework then lists properties of each of these that may interact to affect a system's sustainability (see figures 1.3 and 1.4).

In this chapter, I use these components and the notation Ostrom initially constructed to understand the historical properties and dynamics of the acequias. Additionally, I make a note of where a set of institutional design principles for robust CPR management (Ostrom 1990) apply. There are 8 such principles, and where they are found to apply, the principle number is added in parentheses along with the variable as labeled in Ostrom's framework.

Section 2.1 describes the data collection methods used. Sections 2.2 through 2.6 explore the important historical properties of the acequias as a SES. Sections 2.7 and 2.8 discuss several important outcomes that result, and the interactions among these properties that produce these outcomes. Section 2.9 draws some preliminary conclusions from the analysis.

2.1 Methods

Several sources of data used in this study were produced as a part of a state-run water adjudication 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 elderly acequia members, who were serving or had served as commissioners or mayordomos, were called upon to testify regarding their traditional water-sharing 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. 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 this process, which was originally initiated in 1968. These maps and the accompanying reports are now available online through the OSE website (OSE 2009b).

Two other public sources of data used for this study were a series of satellite images from NASA's Landsat program, which recently have become publically available at no charge, and time series data from several stream gages in the valley placed there by the United States Geological Survey (USGS 2009). Finally, previous work on the acequias in Taos valley proved to be extremely useful in providing historical background (Baxter 1990, 1997; Rivera 1998; Rodriguez 2007).

Additionally, original data collection was conducted through a series of in-person interviews in order to capture important social information that was not available through existing data sources. A total of 44 interviews were conducted, primarily with acequia officials in the valley. All interviews were qualitative and conducted in-person with farmers, usually at their home located on a plot of land they irrigate. The sampling method for selecting interviewees was non-random, involving two procedures. The majority of the interviewees were identified through a comprehensive list of commissioners and mayordomos for each of the acequias in the valley obtained through the Taos Valley Acequia Association (TVAA). The TVAA was initially formed in 1987 to organize the acequias' response to the water adjudication just mentioned. This list contained telephone numbers for each of the officers, and each person listed was contacted first by a telephone call, and a request for an in-person interview was made at this stage.

The reason for selecting acequia mayordomos and commissioners to be interviewed was that they are the most actively involved in acequia operations, and thus are likely to have the most knowledge regarding their own acequia and nearby acequias. An additional snowballing method was used, whereby interviewees identified other farmers or knowledgeable persons who were known to have extensive and relevant knowledge. Several of these persons were also contacted and interviewed. Table 2.1 summarizes attributes of the interviewees. Out of 44 interviews, 13 mayordomos and 30 commissioners were interviewed. Several interviewees were a commissioner or a mayordomo on two systems instead of one, and were counted twice in this table. Ten TVAA board members were also interviewed. The status of being a board member is not dependent on being an officer in a particular acequia, although the two statuses are correlated.

Total interviews	44
Mayordomos interviewed	13
Commissioners interviewed	30
TVAA board members	10
Acequis represented	39

Table 2.1: Interviewee data

I interviewed at least one individual from 39 out of the 51 acequias analyzed in this study. Information on the remaining 12 acequias was obtained from the testimonies, in which the practices and properties of 9 of the 12 are discussed directly, as well as from interviews with farmers from nearby acequias, who frequently had knowledge of the other acequias around them. The properties of the acequias that are reported below are inferred from these interviews and several existing sources that describe the structure and function of the acequias (Crawford 1988; Hicks and Pena 2003; Rivera 1998; Rodriguez 2007). Among these various sources, there is near-unanimity regarding these properties.

2.2 Properties of the acequias as a SES

The following sections explore the properties of the acequias as a social-ecological system. In this analysis, all 51 of the acequias in Taos valley are considered to compose one SES. This contrasts with the analysis presented in chapter 4, where a statistical analysis is conducted with the unit of analysis being individual acequias. A primary focus in exploring the properties of the acequias is to understand how they enable them to respond to droughts, and how they produce a self-reinforcing basin of attraction as described in chapter 1.

2.3 Resource Units (RU)

There are several important features of water as the resource unit being appropriated. It is a liquid at most ambient temperatures and is thus highly mobile **(RU1)**. It is also cohesive **(RU3)** (water adheres to water), which, when combined with its erosive properties that produce self-propagating channels, leads to a heterogeneous spatial distribution[6] **(RU7)**. The temporal distribution of the resource is also heterogeneous **(RU7)**. These properties in turn affect the resource system's storage characteristics **(RS8)**, and the spatial distribution of members who cluster geographically near the resource. This affects the acequias' monitoring and enforcement mechanisms, which will be discussed.

2.4 The resource system (RS)

The sector **(RS1)** of the acequia SES is irrigation. The resource system **(RS)** of the acequia SES is composed of surface water, groundwater, irrigation infrastructure, and arable land. Sub-variables of the sector variable can be introduced to describe the relationships between the various components of an irrigation system. The most important relationship is that between the surface water and groundwater subsystems **(RS1a).** This creates important storage characteristics **(RS8)** that are critical to the acequias' functioning. Additional features of the resource system that are particularly important are the clarity of system boundaries **(RS2)**, the human-constructed infrastructure **(RS4)**, and the predictability of system dynamics **(RS7)**.

2.4.1 RS1a: Surface-groundwater interactions

The interaction between surface and groundwater in the valley is critically important for understanding the functionality of the acequias. Barroll and Burke (2006) and Drakos et al. (2004) indicate that the relationship between the two in Taos valley is quite strong, and that withdrawals or additions in one affect the availability of water from the other.

Fernald et al. (2007) and Fernald and Guldan (2006) have conducted hydrological analyses on acequias in other parts of New Mexico. Their conclusions are very applicable to the acequias in Taos valley. An essential conclusion they come to is that the area between a main river and the main canal off of the river receives substantial portions of groundwater recharge, as observed

[6] This is analogous to how the process of "preferential attachment" in network formation produces unequal distributions of links between nodes. New nodes prefer to attach to highly centralized nodes; likewise, water tends to interact with the landscape in a way that leads to uneven distributions over a landscape.

through raised water tables in these areas following irrigation events. They describe this area adjacent to the river as an "irrigation corridor." In chapter 4, Cox and Ross find that acequias with more access to groundwater along these gaining reaches tend to be more agriculturally productive over time.

The presence of groundwater seepage is illustrated below in Figures 2.1 from Drakos et al. (2004, 8), which shows the gaining reaches along the rivers in the valley. A gaining reach of a river occurs where groundwater seepage adds more water to streamflow than percolation and evapotranspiration take out. Water flow at the end of a gaining reach is higher than it is at the beginning. Much of the gaining portions of the river shown below occur along irrigated fields, indicating that return flow from ditches and groundwater interactions are significant enough to maintain or increase the flow in the river on which they depend. Below this, figure 2.2 shows the depth to the shallow groundwater aquifers in the valley, and indicates that in many portions of the valley, particularly in areas near the acequia ditches, the water is quote close ot the surace, making it more available for surface uses.

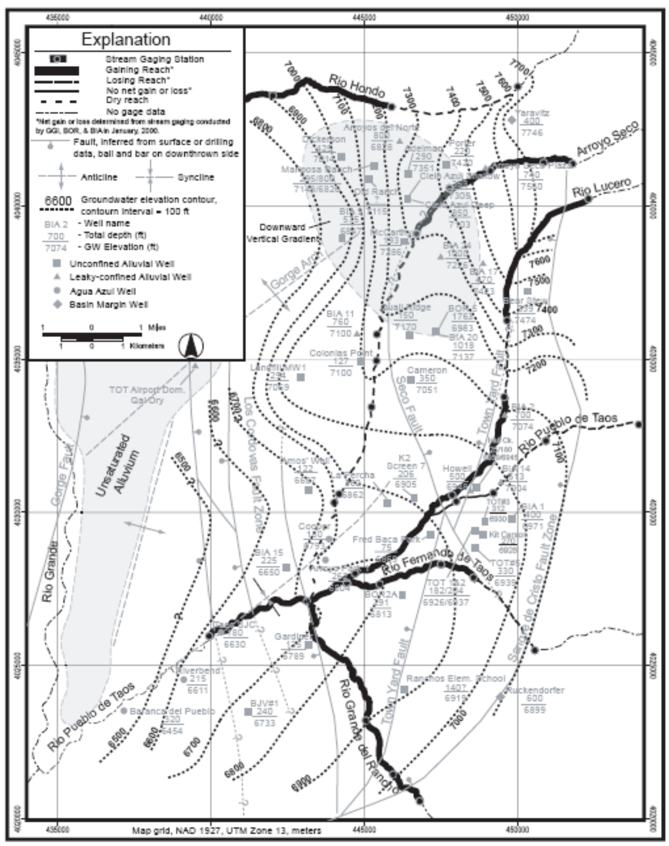

FIGURE 5. Shallow aquifer potentiometric surface map, gaining and losing stream reaches

Figure 2.1: Gaining reaches of major rivers (Drakos et al. 2004, 8)

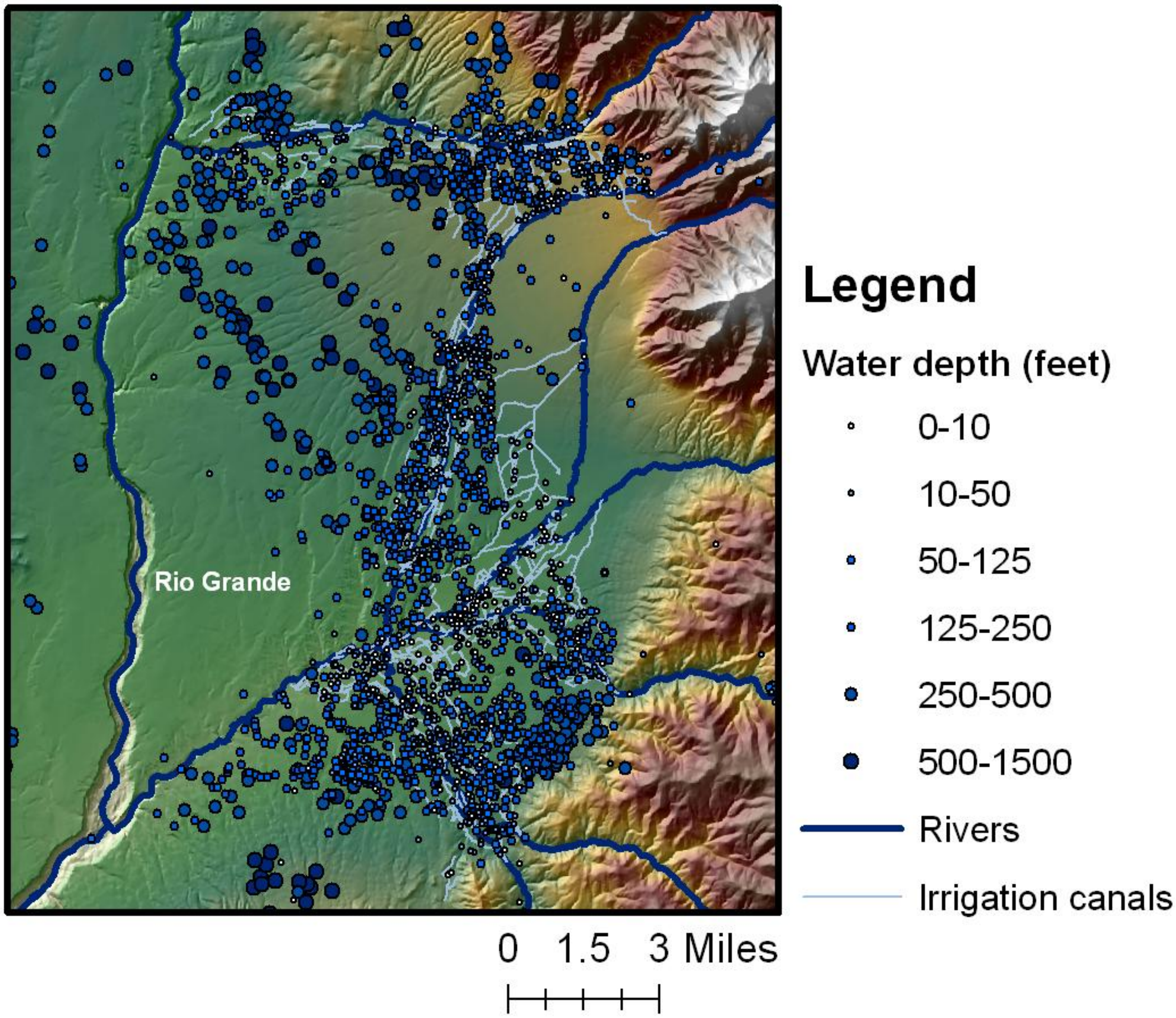

Figure 2.2: Depth to water level in wells

2.4.2 RS8: Storage characteristics

Of the two components of the resource system, surface and groundwater, only one has major storage properties that affect the robustness of the system. Due to the tight connection between the surface and the groundwater, the shallow aquifers in the valley effectively serve to store water after it has percolated down following streamflow and irrigation events. This water frequently seeps back up to the surface for downstream farmers to use. In fact, interviewees frequently reported the availability of water through seepage when the main stream or canal was dry. Rodriguez (2007, 47) describes how these "ojitos" (springs) function:

> *Here, the disadvantage of being at the end of the line is offset by access to a multitude of groundwater and surface water sources: three rivers flowing together with a fourth, in lowlands with a high water table. As the rivers come together at the vortex of Taos basin, their surface water and groundwater*

> *mutually infiltrate and percolate together through the surrounding marsh and pasture. The ojitos along the rivers are what make the basin so fertile and ensure survival during drought.*

2.4.3 RS4: Infrastructure

The infrastructure that the acequias employ includes irrigation ditches and irrigation headworks. The most important feature of these ditches is that they are mostly earthen or unlined (although several acequias in the valley have obtained funds through the county and state governments to line their ditches). Because they are unlined, these ditches allow water to percolate into shallow ground-water aquifers, the significance of which has just been discussed.

An additional feature of the ditches that is important, and ultimately relates to their community structure **(U)**, is their length, which in turn relates to their branching quality, depicted in figure 2.3. The acequias exhibit a fairly high level of branching, and a particular ditch rarely goes too far before it either branches or returns to the river that it initially diverted from. This branching quality reflects the social subdivisions of the larger irrigation system into small community acequias. In network language, the system is modular. This will be discussed later in this chapter. The branching nature of the ditches is a physical reflection of this modular community structure.

This property has been found in other community-based irrigation systems. Coward (1977, 227) discusses how many large, indigenous irrigation systems are divided into subsystems, and how this social decomposition subdivides the physical system, which produces these collective-action problems: "It is important to note that these mini-units are not merely organizational units. Typically, they are also discreet physical units within the larger systems." Coward uses his own observations and several others' (Taillard 1972; Thavaraj 1973) to support this argument. A particular social subunit corresponds to a particular geographic extent of the irrigation system.

An additional feature of the acequias' irrigation infrastructure that needs mentioning is the *desague*, or drainage channel. These channels are located downstream of an acequia's irrigated fields, and return unused or excess flow to the river. A good example of this is illustrated in figure 2.4. The headgate at the right draws water out of the Rio Hondo, which is flowing westward out of the Sangre de Cristo Mountains. The main canal of the San Antonio acequia flows westward, until it ultimately returns back into the river farther downstream.

These drainage channels serve two purposes: first, they partially ameliorate upstream-downstream conflict by augmenting downstream water supplies; second, they help the acequias avoid flooding in their canals and irrigated fields. There are two features that produce flooding events in the valley: first, northern New Mexico experiences late-summer monsoon events with intense rainfall; second, with little vegetative cover to soak up water, much of this rainfall turns directly into run-off.

Finally, regarding the headworks, it is important to note that there are two different kinds, depending on whether the agreement between the ditches or individuals using them is rotational or proportional. Between acequias, both arrangements are used with more proportional than rotational. Within acequias, distribution is entirely rotational. If it is a rotational agreement, the headworks includes some mechanism for partially decreasing the flow to one of the ditches it feeds. It is not a common practice in the acequias to ever stop this flow entirely. If there is a proportional agreement, frequently there is no such mechanism, and the agreement is embodied in a permanent physical division in the headgate.

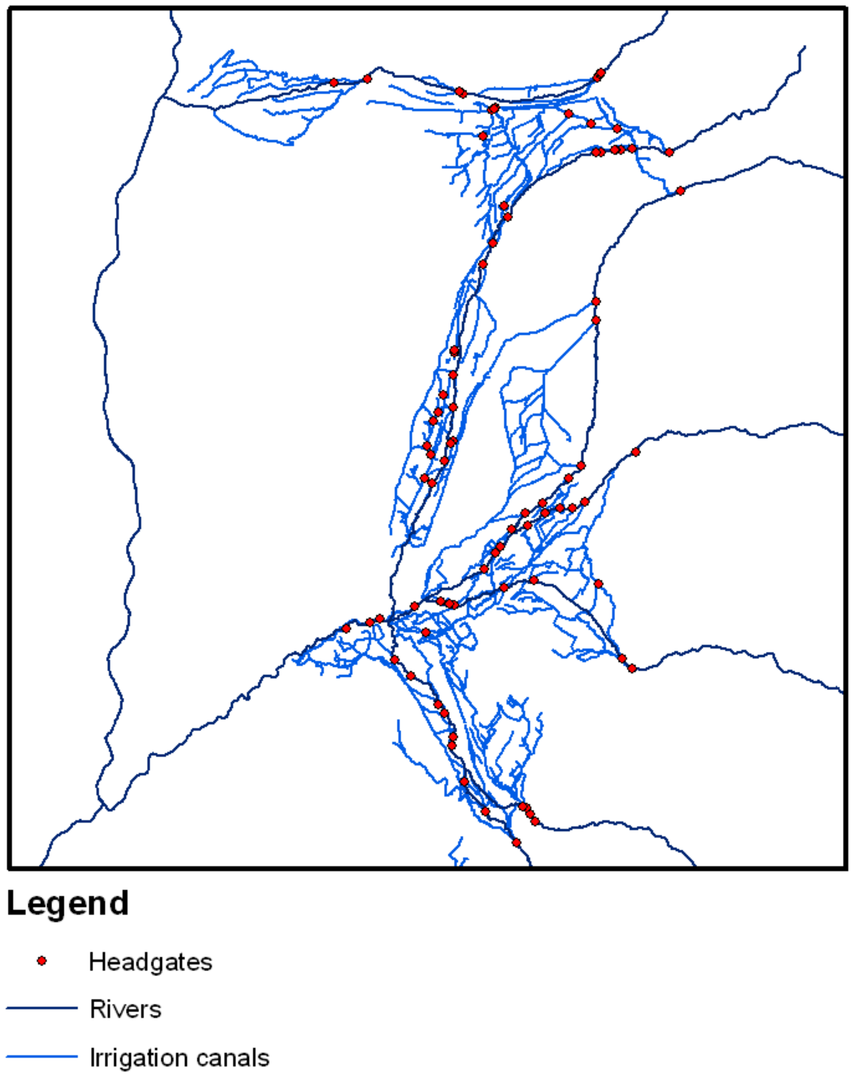

Figure 2.3: Irrigation headgates and canal structure (individual-level canals and headgates are not shown)

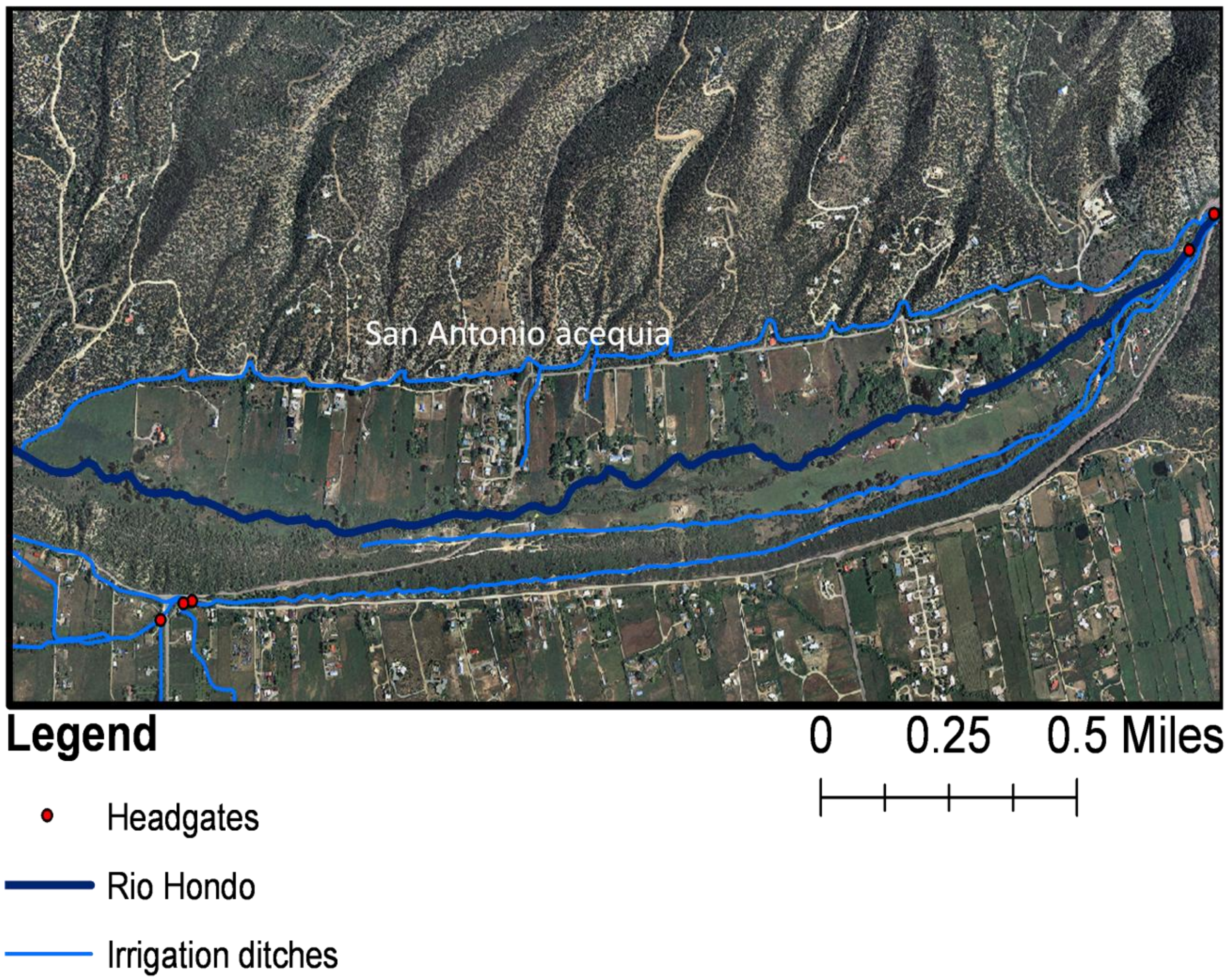

Figure 2.4: Illustration of a desague returning flow from the San Antonio ditch to the Rio Hondo

2.4.4 RS2: Clarity of system boundaries (principle 1)

The boundaries of the resource system are clear for several components of the resource system, including surface water, irrigation infrastructure, and arable land **(RS2, P1)**. The farmers interviewed demonstrate a high level of awareness regarding the limits to each of these resources within their acequias. The boundary for groundwater, however, is unclear. No user in the valley seems to have a precise understanding of the geographic boundaries of the shallow aquifers that play a vital role in the sustainability of the irrigation systems. Knowledge of this system is limited to a basic understanding that water that groundwater seepage ultimately derives from percolation upstream. The exact effects of this fuzzy boundary on the groundwater resource are difficult to specify. However, it is clear that it makes a difference. The property rights arrangements that the acequias have developed largely ignore groundwater sources and do not specify groundwater rights for members as distinct from surface water rights. This seems to indicate that clear resource boundaries are important in forming a property-rights regime.

2.4.5 RS7: Variability and Predictability of system dynamics

Figure 2.5 shows the amount of water flowing through the major rivers upstream of the acequias in the valley in cubic feet per second (CFS). This is the source of the vast majority of water for the acequias, as precipitation levels in the valley only average around 12 inches per year. Figure 2.5 shows a high degree of annual variability in water availability to the acequias. Because of this variability, the amount of water that will be available in one year is not predictable based on the water from previous years. This high variability makes the indirect storage capacity the acequias have in Taos via their underground water resource especially important.

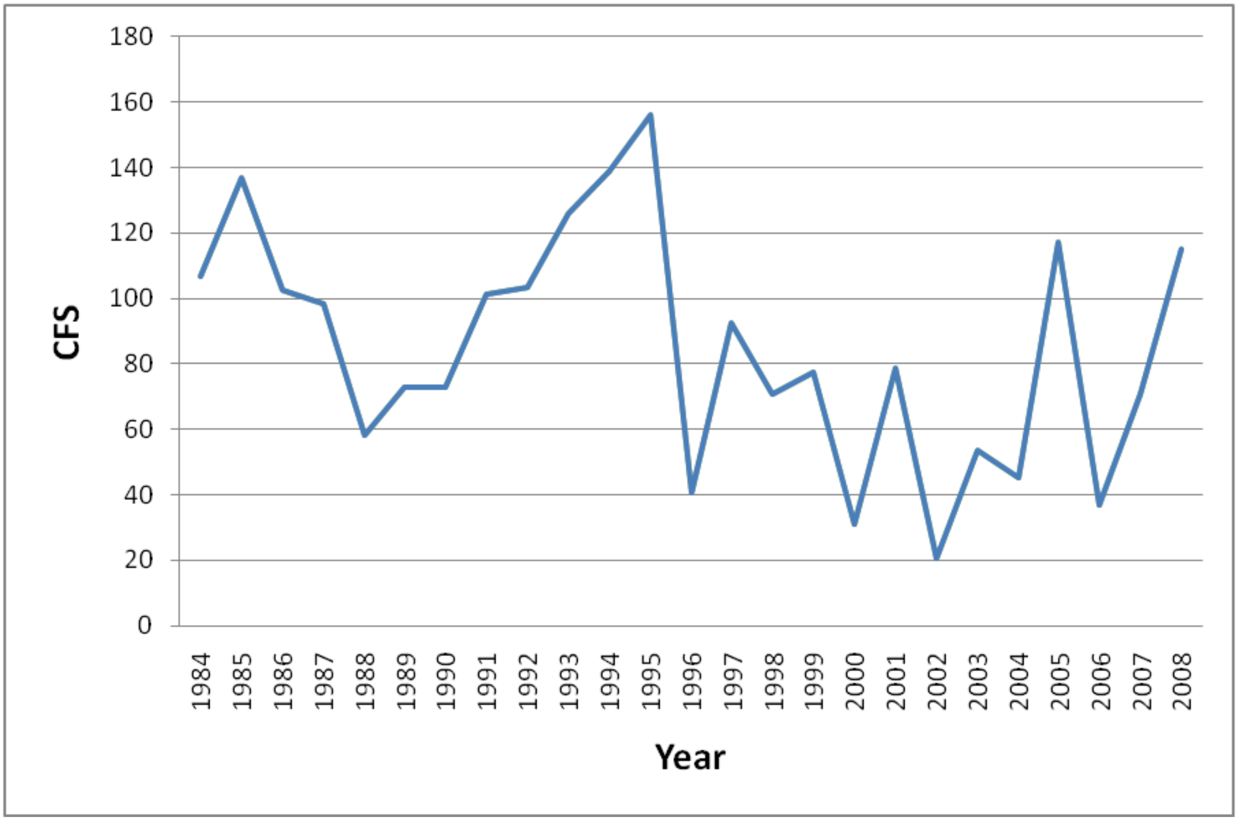

Figure 2.5: Historic water flow values for major rivers

2.5 The governance system (GS)

There are several key features of the acequias' governance system. To begin with, since their settlement, the acequias have been under the jurisdiction of different state entities **(GS1)** that have played important roles in their functioning. Within the acequias, there are several other critical governance components. The most fundamental of these is their property rights system **(GS4)**, specifically, how they distribute varying degrees of authority amongst their officers and members. Secondly, their system of equating costs and benefits is important in maintaining a sense of fairness amongst members with unequal resource endowments **(GS5a)**, and, their rules concerning water distribution **(GS5b)** are one component that facilitates decentralized and low-cost monitoring of infractions within each acequia **(GS8)**.

2.5.1 GS1: Government organizations and conflict resolution (principles 6, 8)

Throughout the acequias' history their external social, political, and economic environment has fluctuated, in large part as a result of the country that held jurisdiction over what is now New Mexico. Initially governed by Spain, the area then shifted to being under Mexico's jurisdiction, and then finally to the United States, first as a territory and then as a state after 1912. The governmental regime in 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 the first three periods, the external government played a crucial role in land settlement and arbitrating disputes amongst waves of settlers.

Since their inception, the irrigation communities in northern New Mexico were subject to the authority of government officials, originally in the form of a provincial governor, appointed by the king of Spain, as well as regional *alcaldes* who distributed land grants to colonial applicants. Baxter (1997, 17) describes the two-level juridical system that resulted from these two roles:

> *Before Mexican independence in 1821, water matters were disposed of under this two-tiered arrangement along with other lawsuits, both civil and criminal. Alcaldes usually heard original complaints concerning inequitable apportionment, acequias damage, or right-of-way location, but petitioners could, if they chose, go straight to the governor. The latter relied on his appointees to conduct investigations and manage routine legal procedures.*

In 1821, Mexico won independence from Spain, which led to several changes, including the transition from governance by local alcaldes to governance by *ayuntamientos*. Baxter (*ibid*, 32) describes their historical role in Taos during the Mexican era:

> *As in other settlements, the Taos ayuntamiento consisted of six regidores (aldermen), presided over by an alcalde constitucional chosen from the membership, and a sindico procurador (town attorney) all elected by popular vote. Charged by the central government to work for the advancement of agriculture, the council regarded responsible resource administration as a primary duty. Water issues most often discussed included allocation disputes between competing settlements, questions of priority, rights-of-way, acequias maintenance, and related problems.*

In 1837, ayuntamientos were abolished, and *juezes de paz* (judges of peace) replaced their water management and conflict resolution functions. Between 1846 and 1848 the U.S.-Mexican war took place, ending in 1848 with the Treaty of Guadalupe Hidalgo. The Kearny Code was passed in 1846 that established a new governmental system for the U.S. territory of New Mexico. This system included "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*. "In Taos County, water apportionment between competing communities proved to be the most difficult problem confronting probate judges. During court sessions, prefects attempted to resolve several long-standing water disputes, some of which had originated years earlier during the Mexican era" (*ibid* 67). Additionally, "in their courtrooms, probate judges considered other water issues besides apportionment between contending groups of users. Frequently acequia management problems, such as enforcement of work regulations, appeared on court dockets" (*ibid*, 69).

There are several decisions that were made originally by probate courts in the territorial period that still hold today, including two agreements between acequias and the local Indian Pueblo, as well as an agreement along the Rio Hondo. In 1852 a hearing was held in the Taos probate court to resolve a dispute amongst the three communities (Arroyo Hondo, Des Montes, and Valdez/Cañoncito) along the Rio Hondo, each holding several acequias. "Having heard both sides Judge Jose Maria Martinez ruled that Arroyo Hondo had first priority in the Hondo, but allowed Desmontes one-third of the river's flow, even in time of scarcity. According to local residents, this apportionment is still observed by the mayordomos of the acequias involved, with Arroyo Hondo's two-thirds divided between its own users and those of Valdez and Cañoncito" (Baxter 1990, 31). This agreement still holds today, and is listed along with other agreements in section 2.6.4.

Two other historical agreements included the Taos Pueblo. The Pueblo is not addressed much in this study, due to issues of inaccessibility (see also Rodriguez 2007) and legal complications arising from the *Abeyta* case (the major point of contention in the case has been the Pueblo's water rights vs. the acequias' rights). Historically, the Pueblo has had both positive and negative relationships with the acequias. The Pueblo Indians predate the acequias in the valley, and as such have more senior water rights. Additionally, they are upstream of several acequias in the valley.

In 1893 Judge Seeds settled a dispute between several acequias in the Arroyo Seco area and the Taos Pueblo. The other agreement is between Taos Pueblo and the Acequia Madre del Rio Pueblo. A series of court hearings were held in the 1870s and 1880s to resolve disputes between the large acequia and the Indians, each time coming to some agreement. While these likely helped allay conflict, the water-sharing agreement that stands today seems to most directly reflect an agreement formed during a self-organized meeting between the acequia members and the Pueblo in 1893 (Baxter 1997).

2.5.2 GS4: Property rights

The acequias employ a mix of property rights arrangements to govern the components of the resource system. Regarding the irrigated infrastructure, at the lowest level, individuals privately own the portion of the ditch that immediately feeds their parcel of land. At the next level, the main canal is the responsibility and property of the entire community. The property rights regarding the land resource are similar. Individuals own their private irrigate parcels, while a certain area around the common property irrigation canal are also common property, and each acequia has easement rights within this area. Historically, the acequias have had pasture lands that were owned in common as well. Surface water is also common property and its appropriation is subject to community rules. As has been mentioned, groundwater, despite its importance, is not governed by any property rights regime. All these property rights hold within acequias. Between acequias, comparatively loose property rights arrangements exist that have been likened by several interviewees to international diplomacy.

Water rights within the acequias are proportional to land rights, and are distributed primarily on a rotational basis, where the mayordomo constructs an ordered list of those farmers who are to receive water in what order. There is a fair level of heterogeneity **(GS4a)** in the amount of land each member owns in the form or private parcels, which translates to an uneven distribution of water rights because the two are proportional. Heterogeneity also exists with respect to property rights along another dimension described by Schlager and Ostrom (1992, 250-251) who construct a hierarchy of property rights. The following list defines these rights:

Access and Withdrawal: "The right to enter a defined property and to obtain the 'products' of a resource (e.g., catch fish, appropriate water, etc.).

Management: "The right to regulate internal use patterns and transform the resource by making improvements."

Exclusion: "The right to determine who will have an access right, and how that right may be transferred."

Alienation: "The right to sell or lease either or both of the collective-choice rights."

Table 2.2 illustrates the types of rights each one of the three main actors in an acequia has. Parciantes have only access and withdrawal rights.[7] Mayordomos have access rights as regular members, but also decide how the water is distributed to right holders (management). 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[8].

Rights	Parciante	Commissioner	Mayordomo
Access and withdrawal	X	X	X
Management			X
Exclusion		X	X
Alienation			

Table 2.2: Acequia property rights distribution

Heterogeneity in an irrigation system with respect to property rights along this dimension creates a hierarchy along what Scarborough (2003, 29) calls the "water management organizational plane." This in turn creates leadership **(U5)** roles for selected individuals and a certain level of centralization in each community. Centralization here means "the internal configuration of

[7] An interesting and problematic development for the acequias has been the granting of alienation rights to members through water markets, where members may sell their rights to non-users, who usually intend to use the rights for non-agricultural purposes.

[8] More recently, as of a 2003 state law, the commissioners may write into the bylaws of an acequia association that formal consent of the membership is required for an individual to transfer/sell their water rights to someone who is not a member of that acequia.

authority among the various irrigation roles" (Kelly 1983, 881). This centralization within communities is different from state-based centralization, and Kelly notes that the two concepts are commonly conflated. This centralization creates leadership roles for those participants with high degrees of authority in the system. The importance of leadership will be discussed in a later section.

2.5.3 GS5: Operational rules

There are several aspects of the operational institutional arrangements that the acequias employ. One extremely important set of rules combine to form what is commonly referred to as the "peon system". This system uses units of labor/resources known as peons, which are also a traditional name for ditch laborers. In this system a peon is both a unit of land and water rights, and a measure of obligation that a right holder has to contribute labor or resources towards maintenance of the acequia. This system maintains a level of proportionality **(GS5a, P2)** between costs incurred by members and the benefits they receive. This is important, as it instills a sense of equality within each community despite the heterogeneous distribution of land and water rights amongst members. Proportionality of costs and benefits and the equity it produces has been previously found to encourage sustained collective action (Ostrom 1990; Cox et al. *forthcoming*).

The actual distribution of water is governed by the mayordomo. The important feature of this system is that it is rotational **(GS5b)**. The mayordomo commonly constructs a list of members who are to receive water in given time period. Only one individual receives water at a time, based on their order on this list. This incentivizes members during their turns to make sure that no one else is using their water, and makes detecting infractions relatively low-cost; if someone else is using water during a particular member's turn, it is obvious that they are breaking a rule. This distribution system effectively creates a rotational schedule for the position of a monitor **(GS8a)**.

2.5.4 GS6: Collective-choice rules (Principle 3)

Each acequia is governed by a set of by-laws that can formally be rewritten only by the commissioners. Elections of commissioners and mayordomos in the acequias commonly occur annually, or in some cases biennially. Thus, while the acequia officers are in charge of and implementing the operational rules, or possibly changing them, these positions are directly accountable to the general membership.

Rule changes and elections within the acequias are decided by popular vote. It is almost universal across the acequias that members receive one vote each, regardless of the extent of their land or water rights. A likely reason for this, like the proportionality between costs and benefits just discussed, is that it maintains a sense of fairness among the members in spite of having their unequally distributed property rights.

In addition, Fischel (2001) notes that a similar voting model (one member, one vote) is used by many local governments and municipalities, and discusses a possible cause that is applicable to the acequias. Under an alternative arrangement that weights votes by the differing amounts of property rights held by members, smallholders (members with fewer rights) could be concerned that largeholders would impose unfair rules on them. Moreover, in communities like local municipalities (and the acequias), smallholders have the vast majority of their assets tied to the physical location of the community, and so would not have any recourse if this were to occur. In this situation, the community may suffer from a holdout problem of getting smallholders to join or remain as members, "which is especially acute when the holdout remains as an immovable neighbor" (*ibid* 37).

The problem caused by this physical proximity would be even more acute in an irrigation system if holdouts are upstream of existing members, and could then disrupt downstream flows. In this context, the voting rules adopted by the acequias can be seen as a development caused in part by efforts of smallholders to minimize the risk of anti-democratic tendencies associated with heterogeneous property rights. Fischel's argument is largely suggestive, and I do not have empirical data with which to judge its applicability to the acequias. However, the commonalities between acequias and municipal corporations as he describes them, both having "plenary powers to tax, take property, spend money, and regulate behavior" (37) in addition to involving members' uninsurable assets, is persuasive and a likely source for future research.

2.5.5 GS8: Monitoring and sanctioning (principles 4 and 5)

There appear to be two primary monitoring mechanisms within the acequias **(GS8a)**. Little direct inter-acequia monitoring appears to be done on a regular basis. The first set of monitoring activities is done by the mayordomo himself within his acequia. The second mechanism occurs when a particular member notices that he is not receiving water at his allocated time. This mechanism is enabled by two features of the acequias: a rotational water distribution system and geographic clustering of private irrigated land parcels. Each member is allocated a particular period during which they receive the entire flow of their acequia; if the flow is not present, the member whose turn it is automatically detects an infraction. Members interviewed frequently reported a practice of "following the ditch" upstream until they found the rule-breaker who was taking water out of their turn. Because the private land parcels that members live on are contiguous and thus not too distant from each other, **(U4)**, and the acequias are not extremely large geographically (which relates back to the branching quality of the infrastructure, **RS4**) this task is not overly burdensome.

Regarding sanctioning, the mayordomo and the commission are in charge of sanctioning offenders, although interviewees seldom reported severe penalties. An initial step is normally taken where the mayordomo may confront a rule-breaker, and may or may not distribute a fine, depending on the extent of the infraction. More serious cases may be brought to the commissioners who act as arbiters of disputes within the acequia. Ultimately, some acequias have reported accessing the court system in order to more severely penalize rule-breakers. This indicates that the court system has retained some of its traditional conflict resolution functions. The sanctioning system can be considered to be roughly graduated **(GS8b)**, where repeated and more several infractions are met with increasingly harsh penalties, although again, such extreme situations seem not to occur very often.

2.6 Users

The user group properties of the acequias are closely connected to the properties of their governance system. An additional variable is added in this section that is not listed in Ostrom's initial version, that being U10: Community/network structure. There is a well-established research program studying social networks, and a newer branch of it that seeks to use network analysis to better understand natural resource management (Bodin et al. 2006; Bodin and Norberg 2005), that forms the inspiration for this addition. Because this structure most directly interacts with the acequia's governance system, and because it affects several other important user group properties, it is presented first, and then is followed by several variables found in Ostrom's initial formulation of the framework.

2.6.1 U10: Community/network structure

The properties of the acequias as a network are important in understanding their institutional properties, which also contribute to their robustness as a SES. A network is a collection of nodes and the links that connect them. Interpreting a community's structure via its network properties requires first defining the nodes and defining what counts as a link. As in all analyses, network analysis depends on the assumption that the insight that is gained by abstracting away basic elements of a system is worth the loss in realism. In this analysis 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. This situation can be seen as a set of overlapping networks each with the same set of nodes but with different types and distributions of links between them. In this situation it can be misleading to define any one of the networks as the structure of the community.

Geertz (1959, 991) describes this situation in slightly different language, describing a set of relationships amongst individuals as a "social plane of organization", where "each such plane consists of a set of social institutions based on a wholly different principle of affiliation, a different manner of grouping individuals or keeping them apart." Geertz makes the important point that metrics of network structure, such as centrality, can often be the result of multiple planes of organization: for example, centrality, where few nodes are the focus of many relationships, can be highest when a particular node is centralized in multiple planes of organization, or in multiple networks.

The acequia farmers in the valley compose 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. The most important properties of the acequias' community structure are its centrality, modularity, and hierarchy. Figure 2.6 displays each of these properties for purposes of illustration. There are several ways in which the acequia farmers interact in order to sustain collective action and manage their water. This analysis focuses on three: water distribution, monitoring, and conflict resolution.

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. 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. This relationship occurs only within acequias: mayordomos do not have authority over members of acequias other than their own.

The one type of link that does occur between acequias that can also be considered to belong to this network is embodied in water sharing agreements between some of the acequias in the valley. These agreements 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.

The monitoring network:

This network is composed of farmers and their relationships as they monitor the behavior of one another with respect to the resource system. There are two basic ways in which this occurs within the acequias. First, the mayordomo monitors the behavior of each one of the members within his ditch. He has this kind of relationship with every single member, but not with members of other ditches. The effectiveness of his monitoring is enabled by his authority as the central distributor of water (see heterogeneity of property rights). Since he is the one who compiles the list that orders who is to get how much water and when, he is in a unique position to monitor whether the water distribution system he manages is being followed.

Secondly, farmers that are geographically proximate to each other tend to indirectly monitor the actions of their neighbors (see a previous 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 ditch to see who is taking it out of turn. 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.

The conflict resolution network:

The acequias internally tend to exhibit a tiered system of enforcement and conflict resolution, where the initial step commonly involves the mayordomo confronting a rule-breaker. In more severe cases, the 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.

Other networks not included:

While these links are important, they obviously do not exhaust the ways in which farmers interact in the valley. Another important source of irrigation-based interaction are annual meetings and ditch cleanings. Additionally, interviewees reported important family and personal ties with other farmers in their ditch and in other ditches. Acequia farmers interviewed frequently described the importance of these relationships in mitigating collective-action problems between communities.

2.6.2 U10a – community centrality

Centrality can be informally 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).

Mayordomos dominate the water distribution and monitoring network. Mayordomos 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, because of their involvement in inter-acequia water-sharing agreements, or *repartamientos* that several groups of the acequias in Taos valley participate in. These links/agreements are triggered by droughts, and will be further discussed in the next section. Finally, mayordomos and commissioners are hubs in the conflict resolution network. These relationships involve internal confrontations and arbitration within acequias.

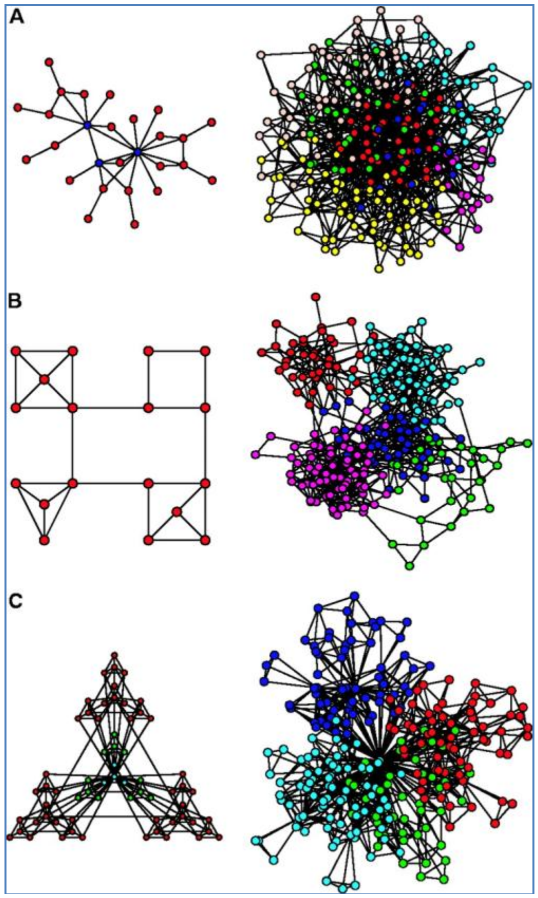

Figure 2.6: Illustrations of network properties. (a) centrality, (b) modularity, and (c) hierarchy. Source: Ravasz et al. 2002, 1552).

2.6.3 U10b – community modularity

In a modular network, nodes 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 among users concerning water distribution, monitoring, and conflict resolution occur within acequias than without; nevertheless, less common but important connections exist between many acequias that enable them to resolve collective-action problems on a larger scale through water-sharing agreements.

Many naturally developed networks form a modular structure to which the acequias seem to adhere. This is not surprising, given the decentralized manner in which they developed. Historical accounts of the colonization of Taos by Hispanic farmers gives a picture of incremental, decentralized additions of new farmers to the area, as opposed to a top-down, centralized process where farmers were placed in predefined groups or communities (Baxter 1997; Ebright 2008). The acequias grew out of a process of incremental settlement; their identities as particular communities in the valley did not precede it[9]. Settlement typically followed the receipt of a land grant from the colonial governor, which was itself dependent on the recommendation of a local *alcalde*, or regional government official. The acequias themselves are typically named after formerly prominent families or individuals from the area, who once played large roles in the settlement or expansion of the area. Rodriguez (2007, 21) describes the process of colonization in Taos valley:

> *Soon more settlements sprang up in these watersheds, as well as on the Arroyo Seco, Rio Hondo, and San Cristobal streams to the north. By the early Mexican period, the number of placitas had more than doubled. These settlements coalesced into bounded, self-identified entities as populations reached the carrying capacities of their respective watersheds.*

The modularity of the overall network accomplishes several things. Primarily, it decomposes the larger irrigation system into subgroups who interact more intimately and frequently among themselves than between each other. Each acequia as a subgroup in this case faces a set of collective action problems imposed by their biophysical relationships as described earlier. However, each group can resolve these collective action problems independently of other groups. This decreases the number of individuals **(U1)** involved in resolving any particular collective action problem.

Smaller groups are better able to resolve collective-action problems due to the decrease in transaction costs involved. 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 is, the costs of monitoring and enforcement are divided up amongst each of the modules, each of which monitors and enforces its own set of internal agreements as described earlier. This subdivision is necessitated by limits imposed by bounded rationality and physical limits on the costs that any particular member of the community can bear: it would be physically and cognitively impossible for one mayordomo to monitor the behavior and actions of the thousands of other farmers in the entire valley.

2.6.4 U10c – multiple levels of organization (principles 8)

When combined, the properties of centrality and modularity can create a hierarchical network with multiple levels of organization (Barabasi 2002), which the acequias exhibit as well. One 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 problem as multiple levels. It was

[9] While acequias as identifiable communities may not have been immediately present, acequias as the mother ditches use by groups of farmers apparently did. A common description of settlement patterns involves two steps: first, building a ditch, and second, building a church.

just discussed that the modularity effectively divides the network up into smaller groups, each of which is able to deal with its own internal collective action problems more easily. The critical next step is at the second level, when the hubs of the network serve as representatives of their individual modules in resolving collective-action problems between modules. In the acequias' case, it is the mayordomos and commissioners as hubs who primarily take part on the inter-acequia agreements that are described below. Barabasi (2002) notes that it is commonly the hubs in a hierarchical network that form the subsequent level of organization above that of the individual modules.

There are two basic types of inter-acequia water relationships. The first is when the acequias share a common diversion point, which physically subdivides the water that is available. Acequias in this situation commonly have a standing proportional arrangement about how much of the water goes where. The other inter-acequia arrangement occurs where the acequias do not share a diversion point, but have a history of communicating during times of shortage because they ultimately rely on the same source of water for their fields. These agreements are generally rotational.

In the Rio Hondo system for example, there is first the level of acequia organization, and secondly there is an agreement between the 8 ditches on the river to divide what is available at the first main headgate three ways, to three separate groups of ditches. This is a standing proportional arrangement that is primarily enforced in times of shortage. Within these groups allocation decisions also need to be made. There are then effectively three levels of organization in this part of the valley.

The following is a list of the formal inter-acequia agreements in Taos valley. While there are other instances of inter-acequia communication in the valley, these are generally referred to as *sobrante* relationships, where a downstream acequia may receive whatever is left over after an upstream acequia irrigates. These more informal agreements do not impose the same level of obligation as the ones listed here, which hold as much force as rules applied within acequias. The units for the proportional agreements listed are unclear, since the acequias have not historically employed a quantitatively precise approach to measuring water rights (see Baxter 2000). The numbers below indicate that, whatever the exact unit, each party receives this fraction of every unit that is available to the larger group.

1. Valdez and Cañoncito ditches (1/3), Des Montes are ditches (1/3), and Arroyo Hondo ditches (1/3).
2. Des Montes acequia (1/3), Acequia del Llano (1/3), and Mariposa ditch (1/3).
3. Acequia del Norte del Cañon (1/3) and the Acequia del Sur del Cañon (2/3).
4. Acequia Madre del Rio Chiquito (2/3) and the Acequia del Monte (1/3).
5. Acequia Madre del Rio Grande (6/10), the Acequia del Finado Francisco Martinez (3/10), and downstream acequias on the Rio Grande del Rancho (1/10).
6. Manuel Andres Trujillo ditch, upper (1/2) and Manuel Andres Trujillo ditch, lower (1/2).
7. Acequia Madre del Prado and Acequia Medio del Prado (1/3), Acequia Madre del Rio Lucero del Arroyo Seco (1/3), and Taos Pueblo (1/3).
8. Acequia Madre del Rio Pueblo (2 days) and Taos Pueblo (5 days).

While all but the final agreement listed here are proportional, several interviewees reported sometimes switching to a rotational system between acequias when scarcity was quite high[10]. The justification for this was that a minimum head of water in a canal is required in order to be of any use, and when not much water is available, dividing it up proportionally may mean that each acequia receives less than this amount.

Additionally, the larger ditches in the valley frequently contain sub-levels of organization that are more informal than the main acequia-level organization. The Acequia Madre del Rio Pueblo, the Aceqiua Madre del Rio Lucero del Arroyo Seco, the Acequia madre del Rio Grande, and the Acequia del Finado Francisco Martinez, four of the largest ditches in the valley, each has a sub-level of organization. In each of these acequias the mayordomo is still ultimately in charge of distributing water, but small sub-branches of the ditch frequently have some degree of self-organization that involves tasks such as conducting their own portion of the annual ditch cleaning along their reach.

Finally, in several of the larger ditches the rotational distribution system is hierarchical, where the mayordomo first distributes to members by sections, and then to individual members within each section (examples include the Acequia Madre del Rio Lucero del Arroyo Seco and the Finado Fransisco Martinez acequia). The geographic lines that separate these sections are commonly referred to as *Lineas*.

To conclude, the community structure of the acequias is extremely important in understanding how they have built up a system that could respond to droughts in a decentralized fashion, by employing multiple levels of governance. This confirms Ostrom's (1990) 8th principle for successful collective action in community-based common-pool resource management. It is worth noting that Ostrom originally had in mind an arrangement slightly different than this one, based on vertical linkages rather than the horizontal (inter-community) linkages discussed here. This multi-level community structure, however, is in part a function of the decisions of higher levels of government, as described in section 2.5.1. These are vertical linkages. As such, the acequias have historically depended on both horizontal linkages between them and vertical linkages to various government organizations in order to adapt and respond to droughts over time.

2.6.5 U1: Number of users

While the number of members in each of the acequias has been increasing in the past several decades, historically the communities are rather small. The average number of members of the 51 acequias as recorded by the OSE hydrographic surveys around 1970 is 40, while the median is 18[11]. A few uncommonly large acequias pull the mean above the median. Scholars have

[10] Such rotational agreements seem to occur between: 1) The acequia Madre del Rio Chiquito and the Acequia del Monte; 2) between the upper and lower Manuel Andres Trujillo acequias; 3) between the Acequia Madre la Loma and the Cortez and Sisneros acequia.

[11] Historic size of the acequias was taken as the number of members established by the original OSE hydrographic surveys from 1969 to 1971. The actual number of members of each acequia is not given by these reports. Instead, a list of the owners of land parcels is given. An assumption was made in calculating the number of members that

shown medium-to-small groups to be better able to resolve collective-action problems than larger groups (Ostrom et al. 1994). These numbers are likely significantly higher in modern-day Taos. One thing that hasn't increased is the geographic area of the acequias. According to the OSE surveys, the average acequia encompasses 254 acres, giving each member an average of 6.35 acres of land. Historically this was augmented by common pastures and forest lands, both of which are largely unavailable to modern acequia farmers.

2.6.6 U2: Socioeconomic attributes

The historical socioeconomic attributes of the acequias are quite different than they are now. Historically, the acequia members have been rather poor, and ethnically and culturally homogenous.

2.6.7 U4: Location

Irrigators have traditionally lived on the private parcels of land that they irrigate.[12] 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 on a rotational water distribution system, facilitates low-cost, decentralized monitoring within each acequia, as discussed previously[13].

2.6.8 U5: Leadership

In the historical basin of attraction, the level of leadership was likely extremely high. The heterogeneity of property rights described earlier creates leadership roles in each acequia community – specifically the mayordomo and the commissioners. The importance of leaders in these communities is that they bear a disproportionate amount of the costs required to produce the required public goods required to maintain collective action and run the irrigation systems.

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. Baxter (1997) reports that historically, positions as acequia officials carried significant authority and respect and were highly sought after. These positions are responsible for a very disproportionate amount of the public good provision that is required to maintain organization and collective action within the acequias.

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duplicate names across several parcels within an acequia represented the same individual, who then owned several parcels. Based on interviews, this appears to be a common feature within the acequias.

[12] In describing the historical settlement of the area, Ebright (2008, 22) states: "It was typical of the independent New Mexican to build his house near his fields, where he could keep an eye out for wild animals or nomadic Indians make off with his crops."

[13] It is worth mentioning that the effects of this system may be lessened somewhat by the fact that some members own multiple parcels, and do not live on more than one; at the same time, having members on multiple ditches will itself partially ameliorate upstream-downstream conflicts, as a member will want to make sure enough water is available for another parcel he owns further downstream.

2.6.9 U8: Dependence on resource

Historically, the acequias' dependence on water as the central resource has been quite high. Survival very much depended on the application of water to land that otherwise could not support much vegetation (as evidenced by the tight correlation between water availability and crop production in table 2.4). Until the last 50 years or so, members did not have a strong connection to alternative sources of income or subsidence other than farming and ranching.

2.7 O: Outcomes

Ostrom (2007) argues that her framework can be used to discover configurations or certain patterns of properties within the various components of a SES as she defines it. This chapter is designed to do just that. The task now, having identified these properties, is to understand how they work together configurately to produce important outcomes.

The acequias have existed in a high desert environment for several hundred years. If we infer sustainability merely from longevity, we can conclude that the acequias are sustainable **(O)**. However, we know that in order for complex systems to persist over time they must adapt to various disturbances. The primary disturbance the acequias have faced in northern New Mexico during the majority of their history has been hydrological drought. In order for the acequias to have persisted for such a long time, their functions must have been robust to these disturbances.

More can be done than merely inferring the robustness of the acequias to droughts from their continued existence in an environment where droughts are common. Using available data we can analyze the relationship over time between the acequias' agricultural productivity, as estimated by a vegetation index known as NDVI, and the amount of water available through streamflow in the rivers of the valley. Since these streamflows represent the primary source of water for the acequias, a deviation in these flows (a hydrological drought) would signify an important disturbance to them.

To analyze this relationship over time, a time series regression was run to conduct statistical tests on the relationships between stream flows and NDVI, to see whether the acequias performance, estimated through average over-time NDVI values, is robust to droughts, as measured by hydrological stream flows. The years from which the data were collected were 1984 to 2008, producing a total of 24 observations (the first year cannot be used due to the inclusion of a lagged variable in the model).

For each year, the average value of agricultural production across the 51 acequias was estimated, as was the total amount of water available in stream flows, measured in cubic feet per second (CFS) for each of the major rivers in the valley. Agricultural production was estimated by applying a vegetation index known as the normalized difference vegetation index (NDVI) to a Landsat satellite image during the growing season for each year (see chapter 4 for a discussion how this was calculated). Stream flows were obtained by stream gage data from gages placed at various points in the valley by the United States Geological Survey.

This model was run to test three specific hypotheses:

H1: The relationship between agricultural production in year y and agricultural production in year y-1 is moderate to weak, and insignificant.

H2: The relationship between agricultural production in year y and streamflow in year y is positive and significant.

H3: the relationship between agricultural production in year y and streamflow in year y-1 is weak and insignificant.

Rejecting H1 would indicate some degree of inertia, where the productivity from one year carries through to the next. H2 being true would illustrate the importance of water as the limiting factor for growing crops in a high desert: when water is not available in a given year, crop growth suffers. H3 is the critical test of the acequias' robustness to droughts. If it is true, then previous droughts will not have strong negative effects on the acequias' current agricultural production: they will be able to recover quickly.[14] H3 being true would also indicate that they do not have extensive storage capacity to take advantage of high water years. These hypotheses were tested by running the following statistical model:

$$NDVI_y = NDVI_{y-1} + CFS_y + CFS_{y-1} + e$$

The subscripts indicate the year of the variable. The three hypotheses are tested by the statistical relationships between the dependent variable, $NDVI_y$, and each of the three independent variables. Table 2.3 presents the results from the regression[15]:

	Coefficients	Standard Error	t Stat	P-value
Intercept	13.014	6.063	2.147	0.044
$NDVI_{y-1}$	0.141	0.238	0.595	0.559
CFS_y	0.211	0.051	4.105	0.001
CFS_{y-1}	-0.024	0.072	-0.333	0.743

Table 2.3: Time series regression results

The relationship between NDVIy and NDVIy-1 is far from significant and H1 is confirmed. Additionally, the statistical relationship between CFS_y and $NDVI_y$ is quite significant, signifying the importance of stream water as a crucial but limiting factor for the acequias. H2 is confirmed. Finally, the coefficient for CFSy-1 is far from significant, confirming H3. Thus, we can conclude that the acequias are quite dependent on yearly water sources, but also they are not affected in subsequent years by large deviations in the amount available in a given year. This means that they are not able to capitalize on high water years with increased agricultural production in subsequent years, but also that they are able to quickly recover from droughts by

[14] While robustness is the term used for this analysis, the ability of a system to return to an equilibrium state quickly after a disturbance was originally defined as engineering resilience by Pimm (1991).

[15] The dependent variable used in the model is actually NDVI * 100, rather than the original NDVI value, which ranges from -1 to 1, in order to obtain interpretable values with 3 significant digits.

returning to previous production levels. Table 2.3 empirically confirms that the acequias are robust to droughts.

We can further understand these relationships if we are aware that streamflows from year to year fluctuate greatly. Because $NDVI_y$ so tightly depends on CFS_y, $NDVI_y$ will tend not to follow $NDVI_{y-1}$ if CFS_y does not follow CFS_{y-1}. To confirm this, one more model was run:

$CFS_y = CFS_{y-1} + e$

This produced the following result as shown in table 2.4:

	Coefficients	Standard Error	t Stat	P-value
Intercept	63.003	18.752	3.360	0.003
CFS_{y-1}	0.247	0.205	1.207	0.240

Table 2.4: Stream flow results

Here again, the relationship is not statistically significant. Streamflows do vary a fair amount from year to year, as does agricultural production

2.8 I: Interactions that explain historical robustness to droughts

Establishing outcomes alone does not give us the level of understanding that we need to make progress towards more sustainable SESs. The components of the framework provide us with the tools to demonstrate the mechanisms behind important outcomes. Figure 2.7 explores the components from the SES framework that are most relevant in explaining the robustness of the acequias to droughts. Each component is labeled based on the variable from the framework it corresponds to, as well as the institutional design principle (Ostrom 1990) that is most relevant.

Figure 2.7 is arranged up roughly in terms of the properties of the SES and its components and processes. It can be understood as a basin of attraction as used in the resilience literature and described in chapter 1. We can begin to understand the functions of the system initially by the close relationship between its governance system and the attributes of the user groups. First, the acequias' network structure is somewhat centralized **(U10a)** (relative to a random distribution of connections).

The officers of the acequias are highly centralized in the networks discussed. This gives them leadership **(U5)** roles, and enables them to produce several important public goods that maintain collective-action in the acequias. These include water distribution, monitoring, **(GS8a, P4)**, sanctioning **(GS8b, P5)**, and conflict resolution **(P6)**, as well as infrastructure provision and the maintenance of user boundaries via monitoring and record-keeping **(P1)**. These officers are able to do this by dint of the specific property rights **(GS4a)** they are granted.

The provision of these public goods is further aided by the high level of dependence on the resource **(U8)** that held in the acequias historically (although not currently). This dependence creates substantial benefits for those involved, which increases the incentives to incur the high costs involved in providing public goods.

The acequias' network structure is also modular **(U10b)**, where each acequia has more frequent and regular interactions between its members and officers than with other acequias, although the latter are also important. The modularity of the structure in the valley increases the number of collective-action problems that must be resolved for the SES as a whole, but decreases the number of participants involved **(U1)** in any one of those collective-action problems. This decreases the transaction costs involved in coming to agreements and resolving these dilemmas, facilitating collective action. The combination of modularity and centrality creates a hierarchical structure **(U10c, P8)** with two levels, one within acequias and one between. This feature also maintains low levels of participants (hubs/officers) involved in resolving collective-action problems between acequias. Interactions between communities have also been historically aided by conflict resolution functions of external government entities **(GS1, P6, P8)**.

An important component of each acequia's water distribution system is that it is time-based or rotational **(GS5b)**, where the amount of time allotted to each member is proportional to the amount of land they own, which in turn is proportional to the amount of labor and/or resources they are expected to contribute **(GS5a, P2)**. This proportionality produces a sense of equality within the acequias, despite their heterogeneous distribution of property rights.

Moreover, this rotational method of distribution 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 **(GS8b, P4).** The costs of this monitoring system are kept low by several other features: 1) the contiguous geographic locations **(U4)** of the users; 2) the branching quality of the infrastructure **(RS4)**, which relates to the relatively small geographic and social size **(U1)**, of each of the communities.

All of this together maintains a sufficient level of social capital and collective action in each of the acequias. This degree of collective action, in turn, can be seen as one step in a series of self-reinforcing processes that maintain the acequias in a particular *basin of attraction*. To reiterate, this is defined as a set of self-reinforcing relationships among the components or state variables of a system. This occurs in the acequias in the following steps.

The acequias maintain a sufficiently high level of collective action (1), which allows them to irrigate with the water that runs through the valley's rivers and directly (and indirectly through groundwater recharge: **RS1a** and **RS8**) increase water availability to their fields (2). This enables the production of crops and livestock, which historically were essential to the economic survival of the system (3). If farmers can produce enough to subsist (4), they will be able to participate in further collective action in the following irrigation season (1), thus perpetuating the cycle. As long as each step occurs, the system can maintain itself in this state.

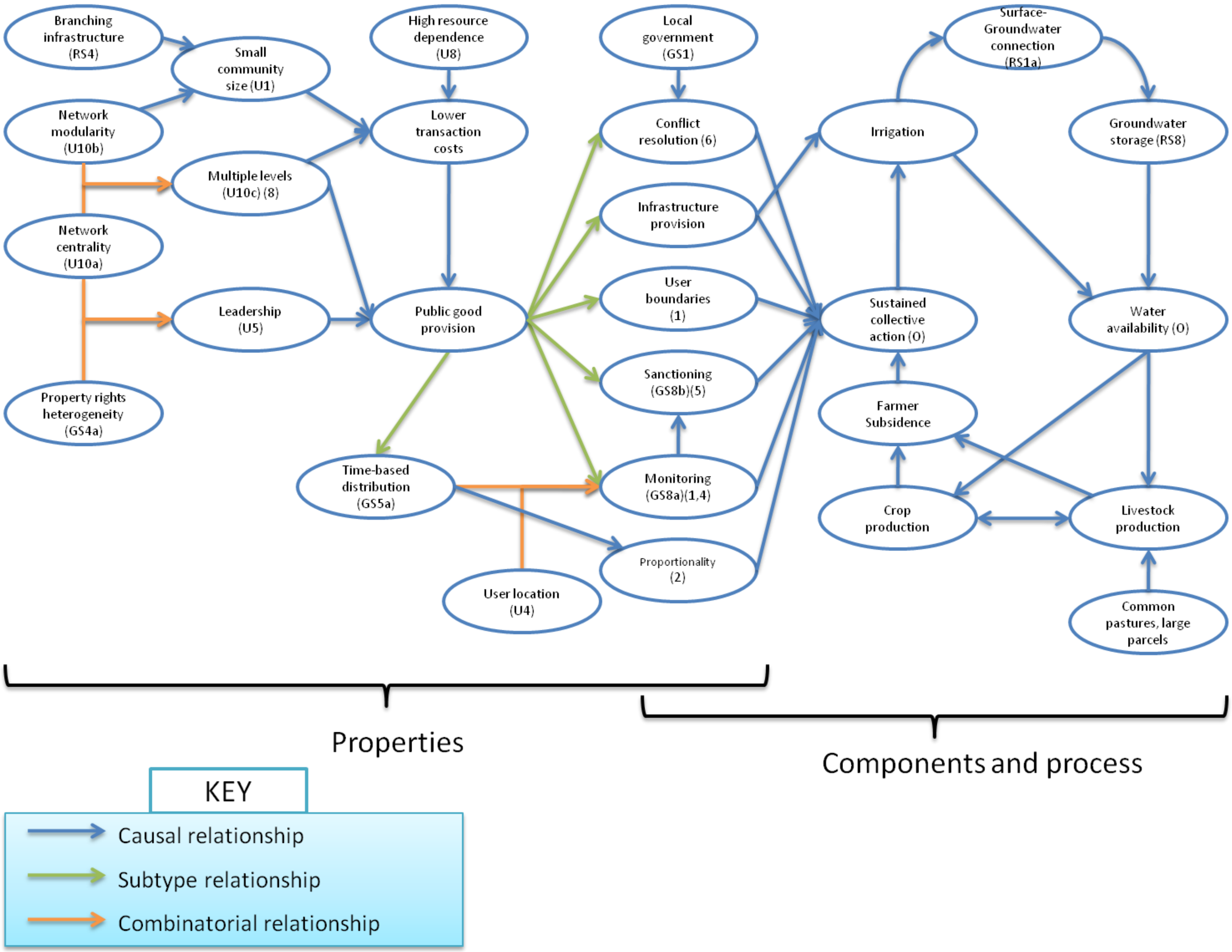

Figure 2.7: The acequias as a social-ecological system: historical basin of attraction.

2.9 Conclusion

Communities of users have proved in many areas to be a vital part of an answer to the problems posed by human-environment interactions. This study confirms a fair portion of the theory that has related certain conditions to the robustness of collective-action in such communities over time. One important example of this is the institutional design principles put forth by Ostrom (1990). Table 2.5 gives a qualitative description of the strength of each of these principles in the Taos acequias' historical configuration. Principles 1 and 2 are broken up into sub-conditions, based on an updated version of these principles (Cox et al. *forthcoming*). Each of the principles is moderately or strongly present.

Principle	Strength in the acequias	Description
1a	Strong	*User boundaries* : Clear boundaries between legitimate users and nonusers are present.
1b	Moderate	*Resource boundaries* : Clear boundaries that separate the appropriated common-pool resource from other environmental phenomena are present.
2a	Strong	*Congruence with local conditions* : Appropriation and provision rules are congruent with local social and environmental conditions.
2b	Strong	*Appropriation and provision* : Appropriation rules are congruent to provision rules; the distribution of costs is proportional to the distribution of benefits.
3	Moderate	*Collective-choice arrangements* : Most individuals affected by the operational rules can participate in modifying the operational rules.
4	Strong	*Monitoring:* Monitors who are accountable to the users monitor the appropriation and provision levels of the users.
5	Strong	*Graduated sanctions* : Appropriators who violate operational rules are likely to be assessed graduated sanctions.
6	Strong	*Conflict-resolution mechanisms* : Appropriators and their officials have access to low-cost local arenas to resolve conflicts among them.
7	Moderate	*Minimal recognition of rights to organize* : The rights of appropriators to devise their own institutions are not challenged by external governmental authorities
8	Strong	*Nested enterprises* : Appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities are organized in multiple layers of nested enterprises

Table 2.5: Application of institutional design principles.

While confirming traditional theory, this chapter also illustrates the importance of considering a mix of social and biophysical properties in order to fully understand the robustness of a SES. This is illustrated most directly in section, 2.8, where I explore the interactions between the properties discussed earlier. In order to understand the contribution of a particular SES property, we must understand how it interacts with other social and biophysical variables. To continue exploring these interactions, future research on SESs will likely benefit from increasingly sophisticated biophysical analysis, and the technologies of GIS and remote sensing as an aid in accomplishing this.

Chapter 3: Understanding Disturbances and Responses in Social-Ecological Systems

Michael Schoon

Michael Cox

3.1 introduction

Disturbances, perturbations, stressors, and pressures are an essential part of theories of social-ecological resilience and institutional robustness (Abel et al. 2006; Anderies et al. 2007; Folke et al. 2005; Janssen et al. 2007). The concern of researchers who deal with such theories generally lies in the characteristics of a system and its capacity to absorb, withstand, resist, or weather a disturbance or set of disturbances. However, few studies clearly articulate exactly what is meant by such disturbances beyond specific cases, or consider in a generalizable manner how outcomes are co-produced by the interactions between disturbances and social-ecological systems (SESs). This chapter intends to help fill these gaps in the literature in three ways: first, by adding a typology of disturbances to Ostrom's (2007) SES framework in order to understand disturbance-response dyads of a SES, second, by using this combination to introduce a simple framework to understand the interactive effects of disturbances on SESs, and third, by applying this to the Taos valley acequias.

If resilience research is to continue its progression from metaphor to measurement, researchers need a means to categorize their observations of interactions between SESs and disturbances (Carpenter et al. 2001). The purpose of this exploration is twofold. First, we want to clarify what may be meant by a disturbance to a SES. In spite of the pervasiveness of the term in resilience literature, few studies clearly articulate a general conceptual definition of disturbance. Instead, "most published accounts of regime shifts involve a single dominant shift defined by one, often slowly changing, variable in an ecosystem" (Anderies et al. 2006, 2). Disturbances come to be identified as whatever happens to change or impact a system for a particular study. Examples include excessive nutrient-loading in the form of phosphorous (Carpenter 2005), and market or population pressures on traditional systems (Agrawal and Yadama 1997). Multiple dimensions along which a system is robust or vulnerable are infrequently considered, as is a more general framework in which they might be compared. This makes cross-case comparisons difficult.

Second, we want to clarify the multiple ways that a system can change and evolve over time. Early research on social-ecological systems often took a static snapshot of a system and overlooked or discounted the dynamic nature of the system. Recent work (Armitage 2005; Janssen et al. 2007) takes a more dynamic approach, and several researchers have begun to develop frameworks for such analyses, which this chapter draws upon for our approach (Redman et al. 2004; Waltner-Toews et al. 2008). In addressing these two points, this chapter starts with the view that to advance our understanding of resilience and robustness, cross-case comparison is required.

This chapter will proceed by laying out the theoretical background of resilience and robustness, SESs, and the relationship between disturbances and SESs. Next, a typology for disturbances and their interactions with SESs is described. The fourth section uses this typology and framework to analyze the acequias in Taos valley. The fifth section addresses some final points and concludes.

3.2 Theoretical Background

3.2.1 SESs, resilience and robustness

It is fair to say that the terms resilience and robustness are not used consistently and with great clarity in much of the literature. Our purpose in this chapter is not to address this problem. However, given that one of our primary goals is to improve the analytical rigor associated with the usage of these terms, a brief discussion is warranted.

The analytical use of resilience began in ecology, mainly within ecological stability theory and was popularized in Holling's (1973, 14) definition of resilience as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables." Within ecology there has been a high level of conceptual confusion regarding resilience and related terms (Grimm and Wissel 1997). Schoon (2005) references several other common definitions of resilience in SESs including the ability of a system to reorganize following disturbance-driven change. One statement we can safely make is that resilience has been associated with the maintenance of a set of relationships in a system, and this sets have been referred to as *alternative steady states, attractors, basins of attraction, domains of attraction, equilibria, regimes, states, steady states*, and *stability domain*s, with varying degrees of mathematical sophistication.

Robustness, which is sometimes used interchangeably with resilience (Levin et al. 1992; Levin and Lubchenco 2008; Newman 2003) but has a distinct scientific lineage, has been defined as "the maintenance of some system characteristics despite fluctuations in the behavior of its component parts or its environment" (Carlson and Doyle 2002, 2539). The desire of predictability, the notion of a performance objective, and the design characteristics that are integral to robustness theory all reflect the engineering background of the concept and the pertinence of the theory toward the designed aspects of a system.

In broad terms, the difference between resilience and robustness may not be that large. Each generally regards the ability of a system to maintain important functions and relationships in the face of a disturbance. For simplicity's sake, we will use the term robustness for the remainder of this chapter, without making any claim to have resolved the issues of which concept should be used when, and what the precise relationship between them is.

3.2.2 The relationship between disturbances and social-ecological systems

Conceiving of SESs and events/disturbances that affect them as distinct objects, we recognize that outcomes are co-produced by the interactions between them. Thus, a system is not robust or resilient as a general principle. Rather, it is robust or resilient with respect to a particular disturbance or set of disturbances. A central tenet of theories dealing with robustness, resilience, and other concepts such as highly optimized tolerance (HOT), is that complex systems become increasingly vulnerable to one set of disturbances when they adapt to another set (Carlson and Doyle 2002; Janssen et al. 2007). "Complex systems must trade off the capacity to cope with some types of variability in order to become robust to others" (Janssen et al. 2007, 309). Levin (1999) and Levin and Lubchenco (2008) offer similar arguments.

Another way of stating this situation is that vulnerability does not disappear. It can be shifted spatially, as in irrigation systems transferring vulnerability from upstream to downstream regions, temporally (into the future), to a different system (shipping hazardous waste to a less-developed country), or to a different type of perturbation (reducing risk of drought at the expense of flooding). In linear control systems, Bode's Law demonstrates mathematically that a system that becomes more robust to disturbances of high amplitude and low frequency also becomes less robust to ones of low amplitude and high frequency, and vice versa. This tenet of control systems serves as a metaphor for how system designers build robustness into some disturbances at the expense of performance or other disturbances.

3.3 A Framework for Studying Disturbances to Social-Ecological Systems

3.3.1 A disturbance typology

Several frameworks and organizing ideas have been proposed for studying SESs, including Gunderson and Holling's (2002) Panarchy concept, coupled human-natural systems (Liu et al. 2007); McLeod and Leslie (2009, 5), Ostrom's (2007) hierarchical framework, Anderies et al.'s (2004) conceptual social-ecological system, Janssen et al.'s network approach (2006), and the robust control framework presented by Anderies et al. (2007).

Defining various types of disturbances that affect SESs is a natural step to take once we have recognized that systems trade-off resilience and vulnerabilities between various types of disturbances. Furthermore, combining aspects of the above frameworks to conceive of a SES as a system made up of interacting components (a network) that receives inputs from an external environment, which is a system itself with its own components and state variables, lends itself to a particular typology of disturbances. These are presented in table 3.1.

The four main types of disturbances we consider are: (1) fluctuation of a flow into or out of a SES; (2) fluctuation in a parameter that affects a SES; (3) a change in the network structure of the system; and (4) a change in the social or ecological connectivity between the SES and the external environment. We will refer to these as (1) a *flow disturbance*, 2) a *parameter disturbance*, (3) a *network disturbance*, and (4) a *connectivity disturbance*, respectively. Table 3.2 provides several examples of each of the four types of disturbances. This provides more instances of how to use the framework and apply it to cases.

Disturbance Type	Properties of Disturbance Type
D1 – *flow disturbance*: Disturbance as a fluctuation in a flow into or out of the system. A flow is something that moves from one entity to another.	Intensity: Average degree of deviation from a norm
	Duration: length of time that the rate deviates from the norm
	Severity: Intensity * duration
	Frequency: 1/X, where X is the average number of time periods in which one such deviation occurs.
	Uncertainty: How predictable the deviation is to user groups
D2 – *parameter disturbance*: Disturbance as a fluctuation in a parameter (state variable) that affects the system	Intensity: Average degree of deviation from a norm
	Duration: length of time that the rate deviates from the norm
	Severity: Intensity * duration
	Frequency: 1/X, where X is the average number of time periods in which one such deviation occurs.
	Uncertainty: How predictable the deviation is to the user groups
D3 – *network disturbance*: Disturbance as a change in network structure of the system (additional or removal of a node or link)	Node addition
	Node removal
	Link addition
	Link removal
D4 – *connectivity disturbance*: Disturbance as a change in the connectivity between the SES and external social or ecological nodes or actors	Increased connectivity
	Decreased connectivity

Table 3.1: Four Disturbance Types

Disturbance	Type	SE	Example
Drought	D1 - Flow	Biophysical	Declining flows due to loss of snowmelt in mountain systems, Aral sea desiccation
Flooding	D1 - Flow	Biophysical	Hurricane Katrina
Change in nutrient flows	D1 - Flow	Biophysical	Excess nitrogen and phosphorous inputs downstream of agricultural regions
Pollution	D1 - Flow	Biophysical	Heavy metals; acid rain
Change in radiative fluxes	D1 - Flow	Biophysical	Global warming
Loss of external assistance	D1 - Flow	Social	Removal of foreign aid programs
Change in trade flows	D1 - Flow	Social	Disintegration of economic trade agreements
Change in salinity	D2 - Parameter	Biophysical	Groundwater salinization following irrigation
Loss of topsoil	D2 - Parameter	Biophysical	Desertification due to overgrazing
Acidification	D2 - Parameter	Biophysical	Ocean acidification due to rising atmospheric CO2 levels
Change in average temperature	D2 - Parameter	Biophysical	Climate change
Changes in chemical nutrient concentrations	D2 - Parameter	Biophysical	Eutrophication in the Gulf of Mexico and Chesepeake Bay
Loss of social capital	D2 - Parameter	Social	Loss of inpersonal trust due to a violent event
Market price fluctuations	D2 - Parameter	Social	Changes in international coffee, crude oil prices
Invasive species	D3 - Network	Biophysical	Asian long-horned beetle
Loss of keystone species	D3 - Network	Biophysical	Loss of sea otters; honeybees
New user groups	D3 - Network	Social	New land owners in the Taos valley acequias
Social node removal	D3 - Network	Social	Assassination or death of leadership
Public infrastructure programs	D4 - Connectivity	Biophysical	Construction of aqueducts
Market demand	D4 - Connectivity	Social	Water markets in New Mexico; international demand for forest timber
Public policies	D4 - Connectivity	Social	Application of governmental regime on local user groups

Table 3.2: Examples of disturbance types

In terms of types of flow and parameter disturbances, we do not consider every fluctuation above or below a mean value to be a disturbance, which would result in interpreting the system being disturbed all of the time. There are several properties of a fluctuation that can be used to evaluate whether it is a disturbance or not. These are its intensity, its duration, and its severity, adopted from Dingman's (2002, 516-517) discussion of drought analysis. The intensity of a drought is its average deviation from a norm for a period of time. The norm is what Dingman refers to as a "truncation level," which need not be the historical average, but could be one standard deviation from the average, for example. The duration is the length of time the variable remains above or below this truncation level, and severity is the cumulative difference, or simply the intensity times the duration.

Although these properties help us explore the dimensions of quantitative disturbances, they do not provide us with an unambiguous criterion for distinguishing "normal" fluctuations from "real" disturbances. This issue is similar to that of determining statistical significance in an analysis. The threshold of a 0.05 p-value is widely used in order to divide statistically significant from non-significant results, but this value is arbitrary and can be misleading; ultimately when a continuum is condensed into a binary variable, information is lost. It is still used, because it simplifies the interpretation of a set of results. In our opinion, however, reporting a p-value both provides more information than a condition of significance, and is not excessively onerous to a reader. Likewise, when discussing quantitative (flow and parameter) disturbances, we should probably worry more about reporting the actual *severity* of the deviation as defined above, rather than whether we are actually characterizing it as a fluctuation or a disturbance. Hence, while using language that implies a binary condition is probably unavoidable, in general we would argue against a binary treatment of quantitative disturbances in this typology. An exception to this would be a case where a system has no previous experience with an input, which is frequently the case with pollutants such as heavy metals or synthetic materials, which we would define as a flow disturbance. In this case severity is mathematically undefined, but the effects of even small amounts of a new input could be quite substantial, where the system's evolutionary history has no adaptive benefit.

A network disturbance is an alteration in the ecological or social network structure of a SES. Scholars focusing on network resilience previously have focused primarily on their resilience to the removal of node, or less frequently, a link (Albert et al. 2000; Ash and Newth 2007; Barabasi 2002; Dunne et al. 2002, 2004). A network is a collection of actors, or nodes, and the links or relationships between them. Any SES would have multiple social and biophysical networks within it, just as it receives inputs from a variety of flows. A common example of an ecological network is a food web, where nodes are species and links are predatory relationships. Other types of connections are possible, such as networks of pollination. The most common way the resilience of networks is tested is by the removal of a node, or sometimes a link. The novel introduction of a new node or link has received much less attention. Such introductions do happen, however. An ecological example of a new node in a food web would be an invasive species. A social example would be a new user group or official who affects how a resource is governed.

Finally, it is important to consider changes in the overall connectivity between the SES itself and external actors, since this may expose the SES to new forms of variation, "such as national governmental policies, technological change, or international economic developments," (Janssen et al. 2007, 312). These may affect, among other things, the users' dependence on the resource and their incentives for collective action. Thus, we include what we call connectivity disturbances. Socially, this type of disturbance maintains the network perspective adopted in the previous one. Social connectivity is a function of particular relationships between actors in a system and external actors. Similar to network disturbances, connectivity disturbances may occur by either the addition or removal of connections between a SES and its external environment.

Connectivity disturbances blur the lines slightly between what may be an external vs. an internal change or disturbance. The scale of the effects is what separates the social or ecological events within the system from disturbances. What is a system change for one analysis may be a disturbance at a smaller spatial or temporal scale. An interesting question to ask is, are the patterns of incidence of and response to various types of disturbances consistent across scales? Researchers frequently comment on the importance of scale in the analysis of SESs (Gunderson and Holling 2002; Silver 2008), and one way that the typology introduces cross-scale effects is through connectivity disturbances.

We recognize that the distinction between the first and second disturbance types and the third and fourth disturbance types is often context- and scale-specific. Thus, we are not arguing that our typology is exhaustive or that different system perspectives would view a disturbance in the same manner. Rather, we argue that the four disturbance types encompass the four principle interaction points between a SES and a disturbance. Furthermore, we maintain that introducing such a typology provides a foundation to begin to study disturbance-response interactions in a SES. In this manner, we have a tool to begin to systematically and empirically examine the evolution of SESs.

3.3.2 A Framework for Studying Disturbances in a Social-Ecological System

We proceed by using the framework developed by Ostrom (2007), along with this typology of disturbances in order to present an adapted framework that enables us to analyze disturbance-response relationships in complex social-ecological systems. Figure 3.1 displays our adapted framework. The labels D1, D2, D3 and D4, correspond to where in a SES we can expect to observe the four types of disturbances just described. D1 is a flow disturbance, D2 is a parameter disturbance, D3 is a network disturbance, and D4 is a connectivity disturbance. The subscript A refers to predominantly biophysical disturbances, and the subscript B denotes predominantly social disturbances.

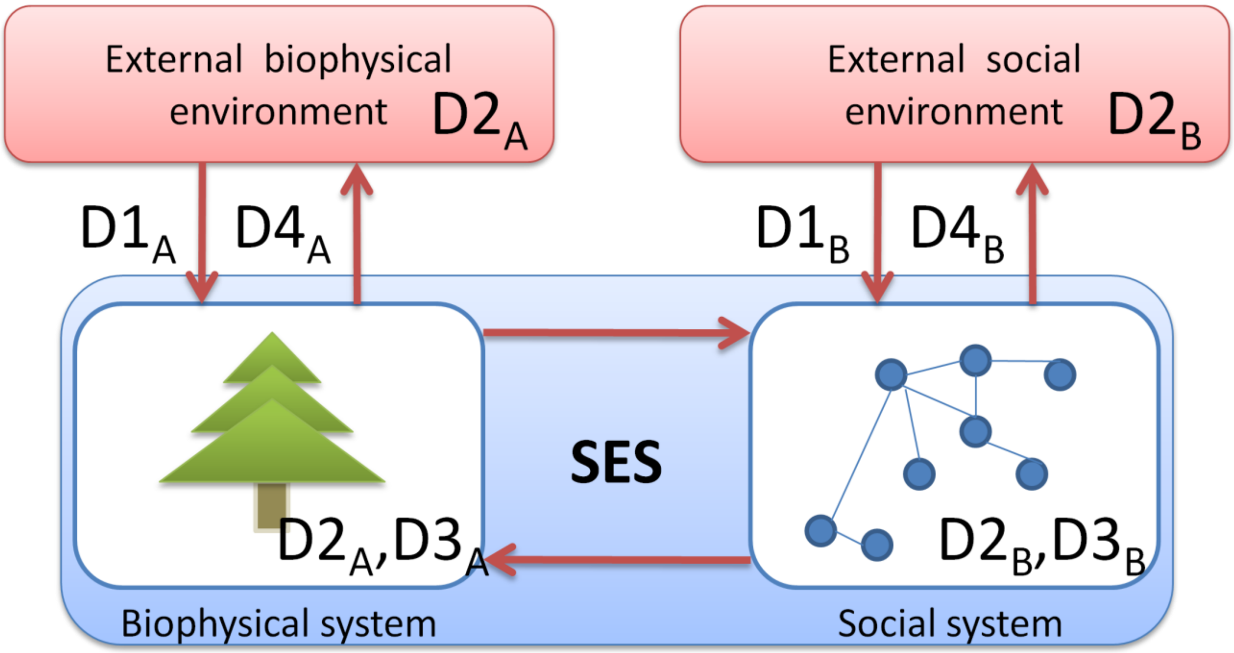

Figure 3.1: Adapted framework

Thus far we have established the possible incidence of multiple types of disturbances upon different components of a SES. However, resilience and robustness are inherently temporal concepts, and this framework can be better understood by thinking about how disturbances and SES responses co-produce outcomes, which, as we will see, can include the incidence of additional disturbances.

The next obvious step in this process is to explore the utility of both the typology of disturbances as well as the framework for over-time analysis of SESs by applying them to case studies. The case study that follows is drawn from the authors' field work and analysis. It illustrates the incidence of the various disturbances outlined in the typology, and examines how the SES changes over time through the interaction of disturbances and the SES.

3.4 Case: The Taos Valley Acequias Study

This section describes the incidence of each of the four disturbance types from table 3.1 on a set of community-based irrigation systems in northern New Mexico known as acequias. The acequias in New Mexico and in parts of southern Colorado are the descendants of the original Spanish colonists, who migrated up along the Rio Grande from Mexico beginning around 1600. As they settled the area, they established networks of canals to irrigate private fields, and common grazing lands to maintain themselves in a high desert environment.

An acequia is a community of irrigating farmers. Each has a well-defined governance structure, led by a mayordomo and a commission usually made up of three commissioners. The mayordomo, as an executive officer, is in charge of deciding how the water is distributed within his or her acequia, and is the primary monitor and enforcer of infractions. The commissioners act as a legislative and judicial body, and are in charge of the formal by-laws of the acequia. They frequently are called on to arbitrate disputes and support the mayordomo in enforcing ditch rules. Water is distributed within each acequia in accordance with a commonly-accepted set of rules, and compliance with community obligations is required in order for an individual to maintain his/her water rights. Such communal obligations are an important feature of the common property arrangements that are common among community-based systems. The focus of this case study is the Taos valley acequias, which were introduced in chapter 1.

Historically, the acequias have had to deal with two *flow disturbances* ($D1_A$): droughts, and secondarily, floods. Using a truncation level discussed earlier of one standard deviation below the historical average, we can look at the hydrographs from the valleys main rivers and state that the acequias do periodically experience hydrological droughts. Using this definition, droughts have occurred in 8 years 1965[16]. Each drought lasted one year.

The acequias have several social and biophysical properties that have enabled them to respond to these disturbances. Their basic challenge is to mitigate upstream-downstream conflict that characterizes all irrigation systems and is exacerbated when water is scarce, where an upstream user's appropriation subtracts from what is available downstream. If these conflicts cannot be resolved, the system will likely deteriorate over time.

Socially, the acequias have adopted a relatively decentralized, multi-tiered governance system, with one level being the institutional arrangements that govern water distribution within acequias, and the second level being the institutions that govern water distribution between them. Instead of having to form and maintain one set of agreements between thousands of farmers at once, this breaks the system down into more manageable social groups which are each able to come to a consensus regarding their own rules. This is the first governance level. Then, key actors (mayordomos and commissioners) from each acequia often take part in decisions made between acequias about how they should distribute water during times of shortage. This social structure serves to minimize the transaction costs involved in maintaining a common understanding of how water is to be divided throughout the entire system, by breaking up the system into subgroups which are then able to independently come to internal agreements, which enable them to act as coherent actors (acequias) which then form agreements that govern the larger system.

Biophysically, two features are important in mitigating upstream-downstream conflicts. The first is the *desague*, or drainage ditch, that returns unused flows to the river from which they appropriate their water. This also helps them avoid flooding problems. Secondly, the acequias' irrigation ditches are unlined, which allows water to flow from their ditches into a shallow groundwater aquifer system in the valley. This water frequently seeps up downstream from where it percolated originally, providing downstream users with additional sources of water. Within the valley there is a strong connection between groundwater and surface water (Drakos et al., 2004). This feature is also noted by Rodriguez (2007). Fernald et al. (2007) have conducted

[16] A hydrological drought occurs when "stream discharge, lake, wetland, and reservoir levels, and water-table elevations decline to unusually low levels" (Dingman, 2002, 509). USGS stream gage data for New Mexico are available at: http://waterdata.usgs.gov/nm/nwis/rt. The drought years (with number of standard deviations below the mean in parenthesis) were 1972(1.26), 1974(1.03), 1977(1.23), 1984(1.23), 1996 (1.1), 2000 (1.36), 2002 (1.64), and 2006 (1.2).

hydrological work on acequias in other parts of New Mexico, and found that groundwater recharge is an important component of these unlined systems.

More recently, the acequias have been experiencing a suite of novel disturbances resulting from economic growth surrounding the town of Taos, which has become a major tourist center. This has had several important effects. First, the acequia members now are fully integrated into local labor markets fueled by the demand for tourism-related goods and services, and do not depend on farming for a living anymore. This is a *connectivity disturbance* ($D4_B$). It drastically lowers their dependence on water, and in turn lowers their incentives to maintain their traditional irrigation practices. This would not be so significant a problem if there were not competing demands for this water from other sources, such as the municipality of Taos.

An additional effect of this growth is a *network disturbance* ($D3_B$), in the form of new members in the acequias. The main problem with new members is that they frequently are unaware of or do not agree to conform to historical rules that the acequias have developed to govern their systems. Cox and Ross (*forthcoming*) in chapter 4 establish through a spatial statistical analysis that acequias with substantial land rights subdivisions resulting from the addition of new members have tended to be less agriculturally productive over time[17].

Finally, the transfer of water out of the acequias, or to new members within acequias, is facilitated by the historical legalization of water rights transfers independent of the land historically associated with the source of water. The State of New Mexico has a functioning, although hardly transparent, water market system. The imposition of this system on the acequias can be seen as an additional *connectivity disturbance* ($D4_B$). In this case, the new connections are market transactions. Clearly, the effects of the various novel disturbances discussed here are synergistic.

As a result of these new social disturbances, several important functions of the acequias have deteriorated. Several farmers reported simply not irrigating when there was no water during a drought, because there was no longer a necessity to do so. Interviewees also reported low levels of attendance at important community events, such as annual meetings and canal cleanings. Interestingly, one interviewee commented that a lack of response by the acequias to these disturbances results from their relative decentralization, which has impeded a coordinated inter-acequia effort to respond. While the central actors in the acequias' traditional network, the mayordomos and commissioners, might have been expected to facilitate this kind of effort, interviewees have also noted that because of the lower dependence on the resource, it has become more and more difficult to find members to fill and carry out those positions.

Additionally, the common grazing system that is an essential component of the acequias' historic persistence and self-reliance has almost entirely disappeared, and the livestock counts of primary

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[17] Agricultural production is estimated by the normalized difference vegetation index (NDVI), which should be considered a proxy for vegetation abundance, although high NDVI values have been well-established to correlate with abundant, healthy vegetation (Lillesand et al. 2008). NDVI is defined for an area as its near-infrared wavelength reflectance minus its red wavelength reflectance, divided by their sum. It ranges from -1 to 1, with higher values associated with higher near-infrared reflectance and lower red reflectance, signifying the presence of more vegetation, as healthy vegetation is highly reflective in near-infrared but poorly reflective in red wavelengths.

grazing animals have plummeted in the last 30 years. These results confirm previous research proposing that community-based systems such as the acequias are frequently vulnerable to social disturbances which involve increases in market demand (Agrawal 1994; Rose 2002).

Additional vulnerabilities that have been introduced as a result of this connectivity are the vulnerability to changes in wage rates (a *parameter disturbance*: $D2_B$), and the loss of the *social connectivity* itself ($D4_B$). The acequias exhibit a property of many complex systems, this being an asymmetry when moving between old and new basins of attraction[18]. The acequias cannot now easily move back to their previous, self-sufficient regime. Due to knowledge and technical expertise that has been lost between generations, such a reversal would now prove quite costly, and they should now be considered to be vulnerable to the removal of this connectivity.

A dimension of these disturbances that is important to consider is their periodicity and cumulative nature, which are related. The historical droughts and floods experienced by the acequias are periodic, and are not generally cumulative. Janssen and Anderies (2007, 51) note that such periodicity, or the lack thereof, affects the ability of a system to maintain its resilience to a disturbance: "A challenge regarding decisions to invest in enhancing robustness it the lack of feedback from previous investments made."

The increase in connectivity that the acequias have contended with is not periodic, but rather steadily increasing in its severity. This is unlike the disturbances they have faced in the past, and does not allow for trial-and-error experimentation that could facilitate a resilient response. Unfortunately, some of the greatest challenges that such systems face seem to be of this nature, whether it is increasing economic and political connectivity that many of them face, or the threat of global climate change. This latter example is not considered here, as it has not affected the acequias in any appreciable way yet. However, it may well semi-permanently affect the flow regime of the rivers the acequias depend on, if, with warming temperatures, much of the precipitation in the mountains fall as rain rather than snow. In terms of severity as defined in table 1, such a *flow disturbance* ($D1_A$) would be many times more severe than a single drought, given the extremely long duration that is likely involved in such a regime change.

Finally, this climate change example reinforces an observation found in the acequias: that one disturbance can introduce others. With the acequias, increasing connectivity also involved a change in the internal network structure of the acequias. With climate change, changing environmental parameters and flows may be accompanied by network disturbances via invasive species, when species' geographic distributions are altered by environmental changes.

3.5 Discussion and Conclusion

The goal of this chapter is to increase our understanding of disturbances and system responses in SESs. Without some type of standardized framework, generalizable findings about the interaction between disturbances and SES responses are extremely difficult to identify. At the same time, such a framework needs to allow for the dynamic nature of SESs and their evolution over time. For this reason, we saw a need to create a new typology for understanding disturbance-response interactions – to better understand system dynamics, to clarify the

[18] This is also sometimes referred to as hysteresis or path dependence.

relationship between specific types of disturbances and how they affect system resilience, and to help identify patterns of disturbance and system responses across a range of cases.

The framework development proceeds in four parts. The first step in this process builds on several existing frameworks for the study of SESs. The new framework takes a network approach to examine the structure of a SES comprised of a social system that includes resource users and a governance system that links with an ecological system of resources. Next, the chapter looks at the four distinct types of disturbances that a SES faces – (1) a fluctuation in a flow into or out of the system, (2) a fluctuation in a parameter that affects the system, (3) a change in network structure of the system, and (4) a change in the connectivity between the SES and external social or ecological nodes or actors. The third step in the process layers these disturbances onto a framework for the SES within a set of nested SESs. Finally, the framework emphasizes how disturbance-response interactions co-produce an outcome as a means to discuss the dynamics and evolution of a SES.

Using this underlying framework, the chapter demonstrates its application through a case study. We feel that such a framework provides generalizable insights into disturbance effects on social-ecological systems and how the interactions between a SES and disturbances reshape the SES over time. These interactions form the crux of resilience/robustness studies. For this reason, we see the use of a common framework that accounts for interactions between a SES and disturbances as a necessary means to gain understanding of the dynamic nature of resilience and robustness.

Chapter 4: Spatial Analysis of the Acequias' Robustness and Vulnerabilities

Michael Cox

Justin Ross

4.1 Introduction

Traditional economic theory and policy analyses have long forecast the destruction or exhaustion of common-pool resources, such as forests and fisheries, unless they are governed by an external authority that is capable of imposing an idealized private or public property-rights system on those who use the resource (Gordan 1954; Hardin 1968). As scholars later began to question these assumptions, attention turned to exploring the conditions under which groups of users can successfully manage a resource using common property rights systems (Agrawal 2003; Feeny et al. 1990; Ostrom 1990).

Irrigation systems are one example of a common-pool resource that is managed by decentralized user groups in many regions around the world. The presence of long-lasting, decentralized irrigation systems has created several puzzles (Mabry 1996; Tang 1992). First, how do such communities resolve collective-action problems inherent in managing irrigation systems over time? Second, how have their organizational adaptations to past disturbances affected their abilities to adapt to novel disturbances in an increasingly interconnected world? Given the abundance of community-based natural resource management systems around the world and the incidence of novel disturbances upon them, answering such questions has practical importance for the management of many natural resources. Additionally, the lessons learned from studying one property rights regime, in this case common property, can potentially be applied to alternative regimes that interact with similarly complex natural resource systems.

This chapter addresses these questions by analyzing 51 acequia irrigation communities in Taos valley of northern New Mexico as social-ecological systems. To understand such systems, both the social system and its biophysical environment need to be addressed. Unfortunately, a gap exists in the literature on human-environment interactions at precisely this intersection, illustrating the difficulty in conducting analyses that involve both social and environmental variables. This chapter addresses this gap using a variety of methodologies and data sources to study the acequias. On-site in-depth interviews and content analysis of historical documentation were conducted, and remote sensing imagery and geographic information systems were employed to generate data that would allow for regression analysis.

This research was conducted to test the following set of hypotheses. These hypotheses are of two types: first, hypotheses H1, H4, H5, and H6 each relate a particular feature of an acequia to its robustness to droughts, which the acequias have periodically experienced their entire time in Taos. Second, H2 and H3 stipulate that the acequias are not robust to two novel disturbance types. Robustness here is the ability to maintain an important performance metric in the face of disturbances, operationalized here as the maintenance of crop production over time. In acequias with favorable characteristics, such as water sharing agreements or small group size, we expect higher levels of crop production per unit area over time as various disturbances occur. In acequias facing greater levels of disturbances they are vulnerable to, we expect lower levels of crop production. The hypotheses are listed here:

H1: Robustness to droughts increases as the number of members in an acequia decreases.

H2: The acequias are vulnerable to the fragmentation of land rights.

H3: The acequias are vulnerable to urbanization.

H4: Access to groundwater as an alternative water source increases acequias' robustness to droughts.

H5: Water sharing agreements increase acequias' robustness to droughts.

H6: Soils that retain water in a dry environment increase the robustness of the acequias to droughts.

The reasons for each of the hypotheses are explored in more detail in the following background section. H1 is drawn from the literature on community-based CPR management. H2 and H3 are drawn from observations and interviews with farmers in the study area, and negative outcomes that have resulted from the processes of land fragmentation and urbanization in other parts of New Mexico. H4 is drawn from previous hydrological work on the acequias. H5 is based on descriptions of water agreements by interviewees and historical testimonies, as well as an analysis of the Kangra irrigation systems of Kuhl in northern India, which arrived at a similar conclusion (Baker 2005). Finally, regarding H6, soil properties are included in order to statistically control for the effects that various soil properties have on local water availability.

The main findings of this study are: (1) The acequias are vulnerable to the disturbances of urbanization and the fragmentation of land property rights; (2) The availability of alternative sources of water via groundwater and water sharing agreements increase the robustness of the acequias to droughts; and (3) acequias of small-to-medium size are more robust than larger acequias.

4.2 Common-pool Resource management and collective action

An irrigation system is an example of a common-pool resource (CPR) which is finite, exhaustible, and which incurs high costs of exclusion to limit the intensity of resource use. These characteristics of CPRs lead to at least two types of collective-action problems: those of resource appropriation and provision (Ostrom et al. 1994). A collective-action problem is a dilemma for user communities due to a divergence between individual and community-level interests. In these situations, the pursuit of individual gain is collectively harmful, and it can be difficult for users to self-organize and act collectively in pursuit of common interests. It is this condition that has historically convinced many scholars and policymakers of a need to impose entirely private or public property regimes to manage CPRs.

An appropriation problem can result in the overconsumption of an exhaustible resource, such as water, when an individual benefits from personal consumption at the expense of the community and the condition of the resource. This is a special case of negative externalities, and is reflected in the commonly observed upstream-downstream relationship between irrigators that pervades irrigation systems. A provision problem, or public good problem, can result in underprovision of the infrastructure needed to appropriate a resource, such as an irrigation headworks. This is essentially a positive externality which occurs because it is difficult to exclude non-contributors from benefiting from, or free-riding on, the efforts of contributors. Individuals may then enjoy the benefits of others' provision without contributing, which lowers their incentive to contribute themselves, leading to socially sub-optimal levels of provision.

Much of the literature on CPR management has focused on common property regimes, where individuals' rights to the resource are contingent upon their continual adherence to community rules and norms. A variety of factors have been hypothesized and tested to contribute to the robustness of cooperation among users facing the social dilemmas posed by CPRs (Agrawal 2003; Ostrom 1990; Ostrom et al. 1994). These include: (1) institutional arrangements and property rights systems; (2) characteristics of the user groups such as their size or heterogeneity; (3) levels of social or economic connectivity within and between user groups or between them and external political and economic environments (Schweik et al. 1997; Tucker et al. 2007).

The main factor from this literature tested in this analysis is the effect of group size. Theory indicates that small to medium-sized groups may be better able to maintain the cooperation needed to manage an irrigation system than large groups (Ostrom et al. 1994). The mechanism behind this relationship is that as the number of members in a group increases, transaction costs involved in monitoring and enforcing agreements among members increase, and to the extent that contractual relationships are formed in order to resolve conflicts, principal-agent problems may be exacerbated due to the increasing costs in obtaining information on the behavior of a large number of members.

4.3 Social-ecological systems, resilience, and robustness

There is now a substantial literature that has related various attributes of social-ecological systems (SESs) to their resilience, robustness, or vulnerability to different types of disturbances. Much of this work has been led by members of the Resilience Alliance (http://www.resalliance.org). Anderies et al. (2004) define a SES as a social system "in which some of the interdependent relationships among humans are mediated through interactions with biophysical and non-human biological units." User groups managing CPRs are one example of a SES.

This literature primarily uses the term resilience when analyzing the sustainability of SESs, and somewhat less frequently the concept of robustness. While sometimes used interchangeably, resilience and robustness have distinct scientific lineages, resilience coming primarily from ecology and robustness from engineering. A common definition of resilience is given by Holling (1973), as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables." Resilience emphasizes the ability of a system to sustain self-reinforcing relationships between its components in the face of a disturbance. Anderies et al. (2004) define robustness as "the maintenance of system performance either when subjected to external, unpredictable perturbations, or when there is uncertainty about the values of design parameters." Carlson and Doyle (2002) give a similar definition of robustness as "the maintenance of some desired system characteristics despite fluctuations in the behavior of its component parts or its environment."

Robustness is used in this analysis of designed irrigation systems instead of resilience because it emphasizes the persistence of a particular feature or function of a designed system, rather than the magnitude of a disturbance an evolved system can face while maintaining a set of self-reinforcing processes or relationships, which can be quite difficult to measure empirically (Carpenter et al. 2001). Because of this it is more amenable to empirical operationalization by measuring the persistence of an important feature the system was designed to maintain in the face of disturbances.

Robustness in a complex system is specific to a level within that system and to a particular disturbance. Social-ecological systems are complex systems constituted by many levels, where the units at each level interact to form units at a higher level. For example, certain farmers in New Mexico interact to form the next level of social organization known as acequias. In a multilevel system such an irrigation system, robustness at one level does not necessarily translate into robustness at other levels. A system may be robust at one level to a particular disturbance, while subsystems at lower levels may not be: a drought may cause several farmers to abandon their fields, while not causing an entire acequia to disintegrate. The level, or unit, of analysis in this study is the acequia. The concept of robustness is particularly appropriate for this study, given the availability of data of a critical system function over time at the geographic scale of an acequia: vegetation production, measured through remote sensing satellite imagery.

Robustness is also disturbance-specific: to meaningfully say a system is robust requires specifying that it is *robust to* a particular disturbance. Long-lasting, community-based irrigation systems like the acequias have successfully adapted to several types of disturbances in the past, particularly droughts. These past adaptations, however, do not ensure that the acequias will persist in the future, particularly in an increasingly connected socio-economic world that integrates local communities into a much larger political and economic system. A central tenant of theories dealing with robustness, resilience, and other concepts such as highly optimized tolerance (HOT), is that complex systems become vulnerable to one set of disturbances when they adapt to another set (Carlson and Doyle 2002; Janssen and Anderies 2007).

4.4 Acequias in New Mexico and Taos valley

Figure 4.1 displays the study area. Taos valley is 2,070m above sea level and encompasses roughly 400km^2. The acequia-irrigated area in the valley is roughly 40km^2. There are varying accounts as to the exact number of acequias in Taos valley, depending on which communities are counted as acequias. The range of the number of acequias in the valley described in interviews and in the relevant literature is roughly 40 to 70. The main use of water in the valley is irrigation. 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, as precipitation in the valley itself is limited to roughly 13 inches per year.

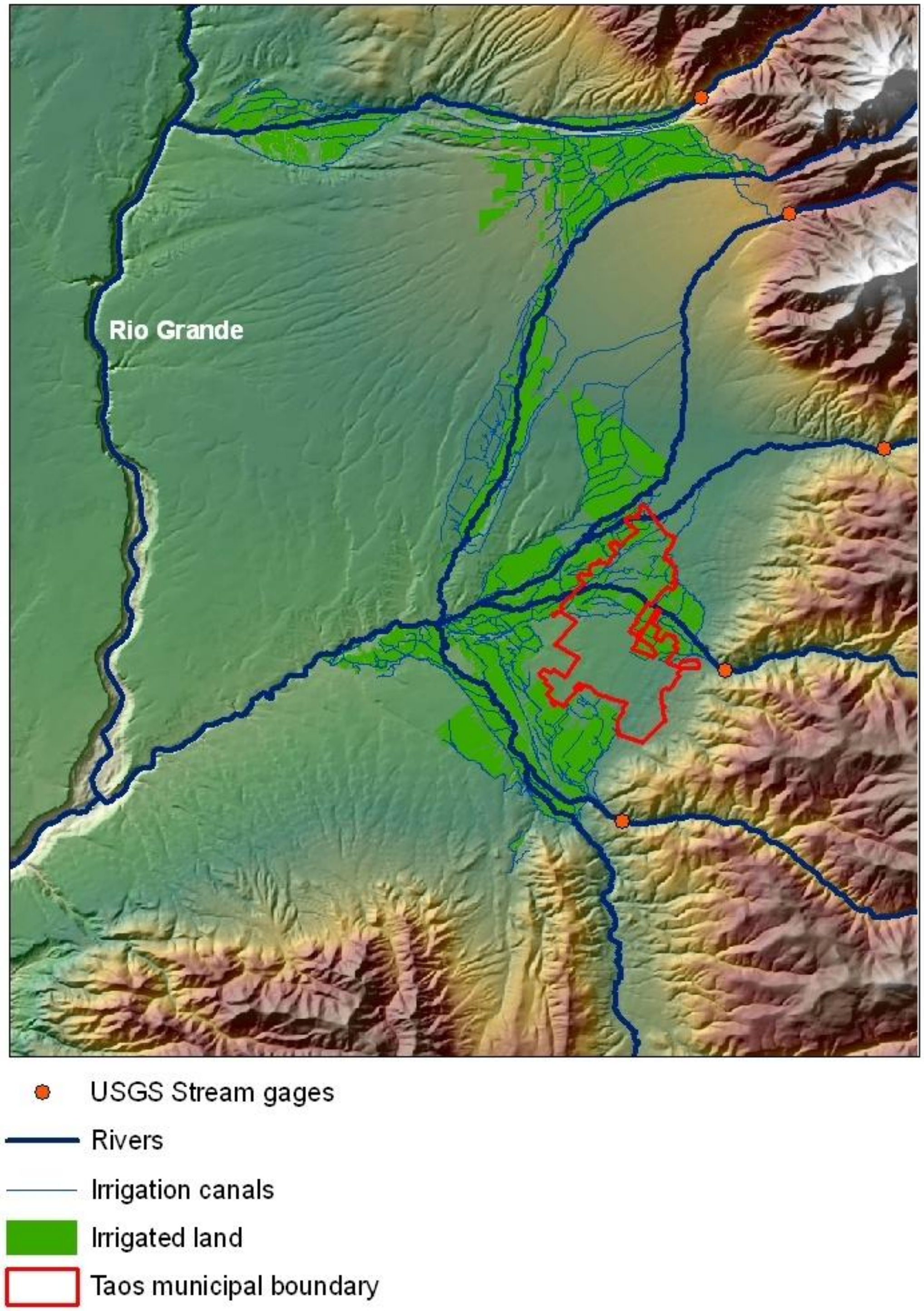

Figure 4.1: Taos Valley

4.4.1 Background

The acequias in New Mexico and in parts of southern Colorado are the descendants of the original Spanish colonists who migrated north along the Rio Grande from Mexico. Acequia farmers still use a form of flood irrigation that is not common in most of the United States, involving the clearing of unlined ditches in the earth to carry water to their agricultural fields. An acequia is the name for a community of users who employ a mix of private and common property rights implemented mostly by three elected commissioners and an executive mayordomo. An acequia is also the name for the main irrigation ditch that a community uses. While each member owns their private parcel of land and the ditch that immediately feeds it, the larger ditch and the water running through it are common property, meaning that to access water, each member must adhere to an established set of community rules. Each acequia also has a biophysical geographic manifestation that is important for this research. This includes an area of irrigated land and the interconnected surface-groundwater system that supplies water to this land via irrigation canals and groundwater aquifers.

As of 1907, acequias are formally political subdivisions of the state of New Mexico. However, water and land rights regimes within acequias are largely independent of the state government. It is the mayordomo who is in charge of allocating water within each acequia, while the commission serves a variety of legislative and judicial roles. When disputes arise between them, no one acequia or acequia official has authority over other acequias. Instead, when droughts occur, mayordomos and/or commissioners from a set of acequias may meet in accordance with historical water sharing agreements. These agreements play an important role in the robustness of the acequias to droughts by supplying water through social means when it would otherwise be unavailable. Similar agreements have been found to increase robustness to disturbances in traditional irrigation systems (Baker 2005).

4.4.2 Acequia hydrology

In order to fully understand how the acequias have historically persisted in a high desert environment, we need to understand both their social and biophysical features. Previous research has been done that has discussed important hydrological properties of the acequias (Drakos et al. 2004; Fernald et al. 2007; Rodriguez 2007). This work has indicated the importance of the surface-groundwater relationship characterized by traditional acequia irrigation methods. There are two components to this. First, it has been found in other parts of New Mexico that acequias recharge shallow groundwater aquifers. “Seepage from ditches and flood irrigated fields performs the important function of recharging shallow groundwater…up to 60% of flood irrigation applications percolate below the rooting zone, and this field percolation in combination with ditch seepage leads to an increase in groundwater levels during the irrigation season” (Fernald et al. 2007, 160). When upstream acequias irrigate by running water through earthen ditches, an important portion of the water they use percolates into the groundwater system. Secondly, groundwater that percolates upstream may seep up to the surface for downstream acequias to use. This attenuates the collective-action problem between upstream and downstream acequias. Interviewees in Taos commonly reported the availability of groundwater through springs, often during times of drought or when upstream acequias did not have any.

4.4.3 The modern situation

While the acequias have historically persisted in a high desert environment with recurrent droughts, their continued survival is very much in question, largely due to increasing population levels across the state of New Mexico. This has had two primary results: new users settling within the acequias' historically irrigated territories, and the expansion of urban centers that compete for water rights, and otherwise adversely affect the hydrology the acequias have depended on for irrigation. Examples of each are found on multiple rivers throughout New Mexico, with the most obvious cases being the areas surrounding Albuquerque and Santa Fe, where acequias that once existed now have entirely disappeared. Both processes are affecting the acequias in Taos valley as well.

New users in an acequia lead to the fragmentation of property rights, as those rights must be subdivided among a larger number of users. Over time, land rights within the acequias of Taos valley have been subdivided, largely as a result of inmigration of relatively wealthy individuals into the valley. "As per a historical analysis of the Assessor's Records, Taos County continues to experience a growth of approximately 230 to 250 new single family residences per year, 90 to 145 new condominium units per year, and approximately 105 to 130 new manufactured homes (mobile homes) per year" (Vigil and Nichols 2009, 42). The majority of this growth is occurring in Taos valley, signifying a disturbance to the acequias there, as newcomers are largely unfamiliar with traditional acequia rules and customs aimed at relieving collective-action problems.

The primary source of urbanization in the valley is the town of Taos, as outlined in figure 1. Urbanization represents a disturbance to the acequias both biophysically and socially. Socially, acequias that are within the border of Taos are more likely to deal with development pressures such as the transfer of their water rights to a newcomer. Biophysically, several acequias in the area have reported that urbanization and development, particularly the paving of new roads and parking lots, have physically disrupted the local hydrology they depend on in order to water their crops.

4.5 Methods

4.5.1 Data collection

Data was collected on seven variables, six independent and one dependent, in order to statistically test the six hypotheses above in a regression analysis. The unit of analysis in this study is an individual acequia, and all variables were calculated at this level. 51 acequias in the valley were analyzed, based on their being listed in hydrographic surveys, as well as interviewees' descriptions of which among these were actually considered to be acequias based on commonly understood definitions. Two databases were constructed to facilitate the analysis: a spatial database used for various calculations, and a non-spatial database that was ultimately used to store fields and values for the econometric analysis. A primary original source of data was a series of hydrographic surveys of the study area, conducted by the New Mexico Office of the State Engineer (OSE) from 1969 to 1971. These maps delineate each of the historically irrigated private parcels of land in the study area, along with the owner, the acequia it belongs to, the acreage, and usually the crop produced at the time. The maps also contain the rivers and main canals for each of the acequias in the area.

The first step in conducting the data collection was obtaining the hydrographic survey reports produced by the OSE. Digitized versions of these maps were obtained by the Taos Soil and Water Conservation District. Since the acequias are the unit of analysis instead of individual members' parcels, the map parcels were aggregated together in the spatial database to form larger geographic units corresponding to each acequia.

An additional source of data was a series of testimonies given by senior acequia officers, testifying to the historic water-sharing practices they have maintained. Both these testimonies and the surveys were produced as a part of a water rights adjudication suit, commonly referred to as the Abeyta case, which was originally filed by the OSE as a part of its mandate to actively manage all of the water in the state. Finally, a set of on-site, informal interviews was conducted with 42 acequia officers (mayordomos or commissioners) from different acequias in order to obtain information on their historical agreements and other information relevant to their robustness or vulnerability to various disturbances.

4.5.2 Calculation of variables

Tables 4.1 and 4.2 describe the variables used in the econometric analysis. Table 4.2 describes various properties of each of the variables, including: which hypothesis the variable is included to test; whether or not a positive or negative relationship is expected between it and the dependent variable, NDVI; whether it is a social or biophysical variable, or both; whether it is a spatial or non-spatial variable; and whether it is a disturbance to an acequia or a property of an acequia. Table 4.3 provides the summary statistics for these variables, as well as for three other single-year measurements of the NDVI variable, whereas the measurement which is in tables 4.1 and 4.2 and used in the main analysis is a multi-year over time average. The following section describes the variables and the methods used to calculate them.

Name	**Description**
NDVI	A spatially averaged estimate of vegetative abundance for an acequia's irrigated area using the Normalized Difference Vegetation Index (NDVI)
Acequia size	The number of members an acequia has historically had, as measured by OSE hydrographic surveys
Land fragmentation	Number of parcels of land in 2006 recorded by Taos County Assessor / number of parcels established by hydorgraphic surveys around 1970
Urbanization	The percentage of an acequia that lies within the municipal boundary of Taos
Groundwater availability	The proportion of an acequia that overlies the "irrigation corridor", where groundwater is more likely to be available
Water agreement	Whether or not an acequia has a formal water-sharing agreement with other acequias
Hydric soils	Presence of hydric soils within each acequia, as identified by the Natural Resource Conservation Service

Table 4.1: Variable descriptions

Name	Hypothesis	Expected relationship	Social/physical	Geography	Type
NDVI	N/A	N/A	Biophysical	Spatial	Dependent
Acequia size	1	Negative	Social	Non-spatial	Property
Land fragmentation	2	Negative	Social	Non-spatial	Disturbance
Urbanization	3	Negative	Both	Spatial	Disturbance
Groundwater availability	4	Positive	Biophysical	Spatial	Property
Water agreement	5	Positive	Social	Non-spatial	Property
Hydric soils	6	Positive	Biophysical	Spatial	Property

Table 4.2: Variable properties

Variable	Mean	STD	Min	Max
NDVI	0.359	0.081	0.202	0.520
NDVI (t=2008)	0.364	0.082	0.205	0.525
NDVI (t=2000)	0.008	0.074	-0.161	0.164
NDVI(t=1985)	0.432	0.073	0.217	0.575
Acequia size	0.397	0.515	0.020	0.244
Land fragmentation	1.185	0.896	0.118	5.382
Urbanization	0.157	0.324	0.000	1.000
Groundwater availability	0.474	0.417	0.000	1.000
Water agreement	0.471	0.504	0.000	1.000
Hydric soils	4.063	2.576	0.000	9.186

Table 4.3: Variable summary statistics

NDVI

NDVI (Normalized Difference Vegetation Index) estimates vegetative production over time for each of the acequias[19]. We infer that high NDVI values indicate high crop production in these areas, as few plants grow in the acequias' irrigated areas other than crops. While irrigation systems as social-ecological systems have both biophysical and social functions, this study focuses on a biophysical estimate, NDVI, for several reasons. First, through remotely sensed imagery, data on this estimate can be obtained for every one of the acequias in the study area over an extensive time period, from 1985 to 2008. Obtaining data on a social variable to the same extent would have been prohibitively difficult, if not impossible. Secondly, it is reasonable to assume that the production of vegetation in irrigated areas is not only a primary biophysical output of irrigation systems, but also a reasonable proxy for a primary social function discussed in the CPR literature: collective-action. The reason for this is that in order to produce crops in a high desert environment, land requires external subsidies of water through irrigation, and due to the relatively low levels of technology available to the acequia members, collective action is still required in order to effectively supply this water to private parcels of land. Thus, crop production indicates important levels of collective-action. NDVI is defined by the following equation:

$$\frac{nir - red}{nir + red}$$

Where *nir* indicates the reflectance of an object or area in the near-infrared wavelengths while *red* indicates reflectance in the red wavelengths of the electromagnetic spectrum. Reflectance is the percentage of light of a particular wavelength incident upon an object that the object reflects. NDVI ranges from -1 to 1, depending on these two values. The higher the value is the more vegetation is likely to be present, as healthy vegetation is highly reflective of near-infrared light and not very reflective of red light. While there are other environmental factors that influence NDVI besides the presence of vegetation, it has been consistently found to correlate positively with biomass (Lillesand et al. 2008). It is worth noting that it is sensitive to precipitation levels, but these do not differ significantly among the Taos Valley acequias.

There are many ways to derive NDVI values for each of the acequias. Our goal was to arrive at one that maintained high conceptual validity with respect to the construct we wish to measure: robustness, where higher NDVI values *over time*, with a mix of disturbances occurring during this time period, are inferred to mean an acequia is more robust to one or more disturbances. Each of the disturbances and the acequias' responses to them occur over time. Thus, a single measurement at a particular point in time would not accurately measure an acequia's ability to maintain agricultural production over time in the face of various disturbances. Instead, a measurement over time is preferred.

To obtain over time NDVI values for each acequia, several steps were taken. First, images from Landsat satellites 5 and 7 were obtained through the United States Geological Survey's (USGS)

[19] Initially, two approaches were used to calculate crop production values for each acequia: image classification and calculating the NDVI vegetation index. After calculating each measurement, the two were found to be highly correlated, strengthening the case for using either one as the measurement of the dependent variable. Ultimately, it was decided that NDVI would be the better of the two metrics.

Global Visualization Viewer (Glovis). Each image contains 7 spectral bands, corresponding to 7 different wavelengths along electromagnetic radiation. Images from the growing season (May to August) of each year from 1985 to 2008 were obtained. These images were only recently made freely available to the public by the USGS. Each of these images had been previously geometrically and radiometrically corrected by the USGS through what they refer to as their Level 1 Production Generation System.

A set of NDVI images was calculated by applying the NDVI equation to the red and near-infrared bands from each of the cells for each Landsat image. Following the creation of the NDVI images, a zonal analysis was conducted on each in order to derive statistics for each of the 51 acequias based on the distribution of NDVI values of the cells within their boundaries. This produced a mean NDVI value from the cells within each acequia from each image.

These steps produced 25 mean NDVI values for each of the acequias, one from each original Landsat image. Each of the 25 NDVI values for each acequia is a spatial average of the NDVI values of all the cells in that acequia's boundary. The final step was to calculate the average of these 25 values for each of the acequias. This produces an over time average NDVI value for each of the acequias as the dependent variable.

There are a few issues to address in the use of spatial and temporal averages for calculating the NDVI dependent variable. The fundamental issue is that multiple spatial and temporal patterns could produce the same average value across space or time, potentially limiting the validity of the NDVI variable as we have calculated it. One acequia could have very heterogeneous NDVI values in the image pixels within its boundary, some high and some low, while another could have a much more even distribution, while producing the same average. The temporal issue is similar: one acequia could have high values early on but then crash, which might produce the same average as another acequia that persists at a lower value over time.

To address the spatial issue, we first took the averaged the values in all 25 NDVI images to produce one over time image, the pixel values of which were NDVI averages from the entire period. We then calculated the spatial average, standard deviation, and coefficient of variation of NDVI values for each of the 51 acequias. The average here is identical to the dependent variable previously discussed, calculated now by taking the temporal average before the spatial average, instead of the other way around. The coefficient of variation (CV) is the standard deviation normalized by the average, and it gives us an idea of how much spatial heterogeneity there is in the NDVI values of the pixels form the overtime NDVI image. If the CV is too high, then using an average as a summary of the data becomes less valid. Multiplied by 100, units for the CV become percentages of the mean. The average value of the CV across all 51 acequias is 27.7%, its standard deviation is 11.5%, its minimum is 10% and its maximum is 52%. These descriptive statistics for CV indicate that, while it has its limitations, using the average of spatial values is a reasonable approach to take.

Finally, to address the issue of the temporal average, we plotted the NDVI value for each acequia for each year to observe whether there were significant differences in their patterns over time. If an acequia, for example, produced large amounts but then suffered a crash in production, this should not be valued as indicating the same level of sustainability as an acequia that maintains a lower, but relatively constant, NDVI value over time. The plots did not reveal significant deviations in temporal patterns for NDVI over time.

Acequia size

Historic size of the acequias was taken as the number of members established by the original OSE hydrographic surveys from 1969 to 1971. The actual number of members of each acequia is not given by these reports. Instead, a list of the owners of land parcels is given. An assumption was made in calculating the number of members that duplicate names across several parcels within an acequia represented the same individual, who then owned several parcels. Based on interviews, this appears to be a common feature within the acequias.

Land fragmentation and urbanization

The index of land fragmentation was calculated by comparing the number of individual parcels within each acequia as established by the hydrographic survey reports with the number of parcels in the same area as calculated by a spatial database produced by the Taos County Assessor's office in 2006. As the parcels from the hydrographic surveys were originally used to construct the polygons for the acequias, these lie perfectly within them, whereas the parcels from the Assessor's data office do not. Therefore, in order to calculate the number of new parcels within each acequia boundary, centroids were first calculated for each new parcel, and the number of centroids lying within each acequia was then calculated to obtain the new number of parcels. The variable itself is simply the new number of parcels divided by the old number of parcels within an acequia's boundary. A higher value indicates a greater degree of land right fragmentation.

In order to calculate the extent to which an acequia is facing the effects of urbanization, the percentage of that acequia's area that lies within with the municipal area of Taos, as outlined in Figure 4.1, was measured. This was used because the processes of urbanization are occurring much more intensely within this municipal boundary than without. Acequias within this boundary are much more subject to these forces.

Groundwater availability and water agreements

To measure the extent to which groundwater is available to the each of the acequias, a geographic buffer was created around each of the main rivers in the area and extending to portions of the main irrigated ditches in order to simulate an "irrigated corridor" that Fernald et al. (2007) describe. It is within this corridor between the river and a main canal that they report important groundwater recharge occurring following an acequia's irrigation. The percentage of each acequia's irrigated land area that lies within this corridor was calculated to obtain a measurement for this variable.

The water agreement variable is binary, being a 1 for an acequia does have any agreements and a 0 if it does not. In order for this variable to be coded as a 1, the acequias involved needed to exhibit a relatively formalized understanding amongst each one of them: more ad hoc or member-level arrangements were not counted. The source of data for this variable was the Abeyta case testimonies and on-site interviews with farmers.

Hydric soils

Different soil conditions are potentially important in determining the amount of crops different acequias are able to produce over time. The source of information for this variable is the Soil Survey Geographic (SSURGO) Database, produced by the Natural Resource Conservation Service within the United States Department of Agriculture. This is a spatial database based on geographic "map units" represented as polygon features in an Arcgis shapefile, which are connected to tabular information in an Arcgis geodatabase.

In order to determine which soil property or properties to include in the analysis, spatial analyses were conducted in order to determine whether certain soil properties were positively correlated with NDVI values. Several properties from the SSURGO database were found to affect the NDVI values within different areas of the valley. These include soil texture, soil drainage class, cation exchange capacity, hydric conditions, distance to underlying water table, and irrigation land capability class[20]. The most important of these seems to be the presence of hydric soils, where hydric soils have higher NDVI values than non-hydric soils. Hydric soils have the following definition (NRCS 2009):

> *The concept of hydric soils includes soils developed under sufficiently wet conditions to support the growth and regeneration of hydrophytic vegetation. Soils that are sufficiently wet because of artificial measures are included in the concept of hydric soils. Also, soils in which the hydrology has been artificially modified are hydric if the soil, in an unaltered state, was hydric. Some series, designated as hydric, have phases that are not hydric depending on water table, flooding, and ponding characteristics.*

Given Leibig's law of the minimum it is not surprising that, in an area with severe water scarcity, that hydric soils would be so positively correlated with increased vegetation in irrigated areas. Figure 4.2 shows the result of the zonal analysis for hydric soils. There are three categories: all hydric, partially hydric, and not hydric.

[20] "Land capability classification shows, in a general way, the suitability of soils for most kinds of field crops. Crops that require special management are excluded. The soils are grouped according to their limitations for field crops, the risk of damage if they are used for crops, and the way they respond to management" (Text from ArcMap Soil Data Viewer application produced by the Natural Resource Conservation Service). The classes range from 1 to 8, with higher numbered classes representing increasing limitations on land use for irrigation.

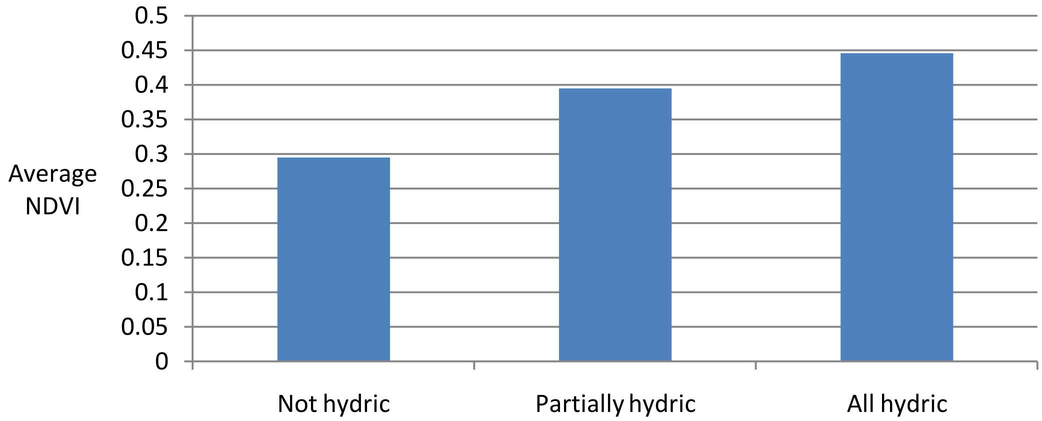

Figure 4.2: Relationship between hydric soils and NDVI

Additionally, it appears that the presence of hydric soils is an important factor in what makes other soil properties correlate with NDVI values. Table 4.4 gives a representative example of the patterns found. For this table, "hydric" is a weighted average of the hydric soil conditions in the zone defined by a particular soil property, where "not hydric" is coded as a 0, "partially hydric" is coded as a 1, and all hydric is coded as a 2. For soil texture and the other soil properties analyzed (including irrigation capability class, drainage class, cation-exchange capacity, and distance to water table) higher NDVI values are positively correlated with increasing hydric values within the different soil categories.

The higher hydric and NDVI values within each soil category seem to associate with increased water retention and/or availability. Regarding soil texture, which is the proportion of particle sizes within a volume of soil, larger particles within soils are accompanied by increased porosity, which increases the ability of water to percolate below rooting depth. Thus, water will be better retained by soils with finer particles. The four categories of soil textures found within the acequias in Table 4.4 are listed in order of increasing NDVI values and hydric values, but also in terms of decreasing average particle size. Loam is a mixture of sand, silt and clay, with sand particles being the largest and clay particles being the smallest. Clay loam has larger amounts of small clay particles and less of the other two and thus smaller particles on average, while silty clay loam has just as much clay as a clay loam, but less sand more silt than a clay loam.

Texture	Hydric	NDVI
Very gravelly loam	0.00	0.26
Loam	0.00	0.28
Clay loam	0.62	0.36
Silty clay loam	1.29	0.43

Table 4.4: Categories of acequia soil texture

As a result of this analysis, the hydric property of soils was considered to be a reasonable summary of various soil properties insofar as they affect vegetative growth in those areas. The final step in calculating this variable was to translate hydric properties of SSURGO map units, coded as 0, 1, and 2, into acequia-level attributes. To do this, an average "hydric" value was calculated for each acequia, weighting the values of each of the three hydric classes by the percentage of the acequia's land area they occupy.

4.6 Relationships between independent variables

Table 4.5 provides the Pearson univariate correlations between the independent variables[21].

[21] Table 4.5 also provides preliminary evidence that multicollinearity between the independent variables is not a concern, and this is further supported with variance inflation factors and condition index diagnostics from Belsey et al. (1980).

	NDVI	Acequia size	Land fragmentation	Urbanization	Groundwater availability	Water agreement
NDVI	1.00					
Acequia size	-0.33	1.00				
Land fragmentation	-0.38	-0.02	1.00			
Urbanization	-0.15	-0.01	0.06	1.00		
Groundwater availability	0.51	-0.37	-0.28	-0.14	1.00	
Water agreement	-0.05	0.52	-0.25	-0.05	-0.39	1.00
Hydric soils	0.48	-0.54	-0.03	0.25	0.51	-0.39

Table 4.5: Pearson R correlation matrix

The relationship between groundwater availability and water agreements in particular is worth discussing. Each variable accomplishes a similar function: providing a source of water to an acequia that it needs when regular surface water resources are scarce. Noting that acequias that have less access to groundwater are more likely to experience overall water scarcity, and that water agreements are historically formed in a response to water scarcity, we would expect there to be a negative relationship between these two variables. Indeed, this is what we find in Table 4.5 (-0.39). Additionally, the average value of groundwater availability for acequias involved in a water sharing agreement is 30.4% (meaning that 30.4% of their area overlies the irrigation corridor, where groundwater is more likely to be available), while the average value for acequias not involved in a water sharing agreement is 62.4%. The difference between the two means is significantly far from 0, with a p value of 0.0024. This indicates that the acequias involved in agreements to obtain water during shortages have significantly less access to groundwater than those that do not, which is a plausible reason for why they have those agreements.

4.7 Econometric models and results

The first column of Table 4.5 provides the pairwise correlations with NDVI and the other independent variables. Each of these correlations confirms the related hypothesis, except for the very slight negative correlation (0.05) between *water agreement* and *NDVI*, which implies little to no relation at all. Following this initial analysis, we turned to the regression models. Here, the vegetation index represented by NDVI for acequia i is assumed to be a linear function of the previously discussed independent variables:

(1) $NDVI_i = \beta_0 + \beta_1 AcequiaSize_i + \beta_2 LandFragmentation_i + \beta_3 Urbanization_i + \beta_4 GroundWater_i + \beta_5 WaterAgreement_i + \beta_6 Hydricsoils_i + \varepsilon_i$

Table 4.6 provides the OLS estimates of the Equation (1) model. The OLS model fits the data well, explaining 47 percent of the variation in NDVI. Also provided in the first two columns of Table 4.6 is the Jarque and Bera (1987) test for normality of the dependent variable, the Koenker and Bassett (1982) test for homoskedasticity, and a set of spatial regression diagnostics. Both the Jarque-Bera test and Koenker-Bassett test fail to reject their respective null-hypotheses, so attention is turned to the motivations of the spatial diagnostics.

	Ordinary Least Squares	Spatial Error Model
Constant	0.316 ***	0.303 ***
	(0.034)	(0.032)
Acequia size	-0.021	-0.032 *
	(0.023)	(0.019)
Land fragmentation	-0.023 **	-0.016
	(0.011)	(0.010)
Urbanization	-0.051 *	-0.052
	(0.030)	(0.032)
Groundwater availability	0.042	0.058 **
	(0.029)	(0.026)
Water agreement	0.030	0.045 **
	(0.023)	(0.021)
Hydric soils	0.013 ***	0.011 ***
	(0.005)	(0.004)
λ		0.372 **
		(0.186)
Sample Size	51	51
R^2	0.474	0.529
JB	1.630	
KB	1.340	
LM-Lag	1.140	
LM-Error	3.269 *	
S-H Test	8.705	

Notes: Abreviations: Jarque-Bera test for normality of dependent variable (JB), Koenker-Bassett test for heteroskedasticity (KB), Langrange Multiplier (LM), Spatial Hausman Test (S-H).
Statistical significance indicated at the .01, .05, and .10 level by ***, **, and *, respecitvely.

Table 4.6: Regression results

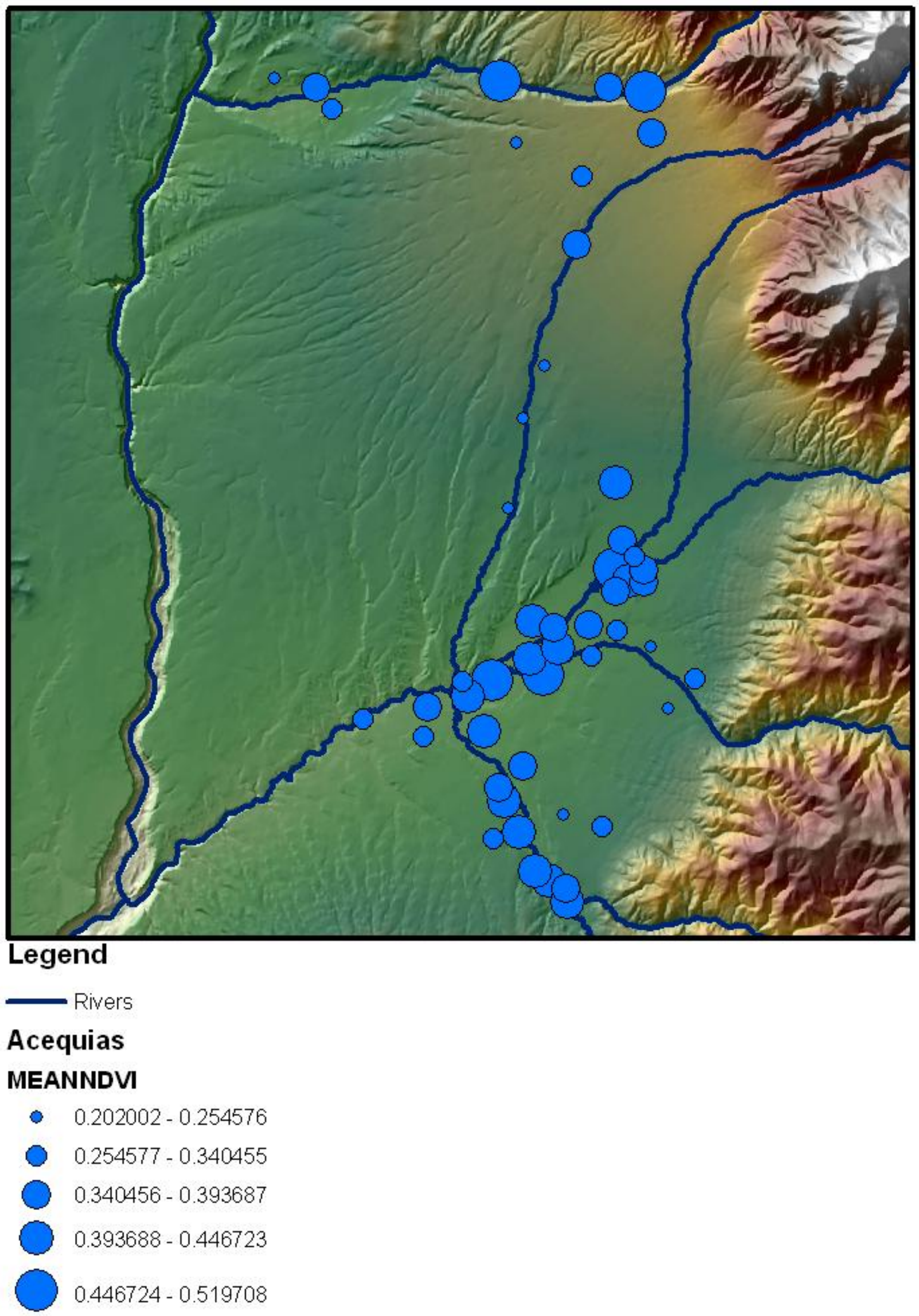

Figure 4.3: Spatial view of vegetation index (NDVI)

Intuitively, CPR-related social dilemmas are spatially oriented problems. That the individually rational behavior amongst each acequia might be problematic for all neighboring acequias could econometrically manifest itself as spatial autocorrelation. Figure 4.3 overlays a bubble plot of the NDVI on a surface map of the acequias in the Taos valley, and visually there appears to be clustering of similar values among neighbors. In this situation, ordinary least squares could be biased, inconsistent, or both (Anselin 1988). This can be modeled as either the spatial autoregressive model (SAR):

$$(2)\ y = \rho W y + X\beta + e,$$

or as the spatial error model (SEM):

$$(3)\ y = X\beta + v$$
$$v = \lambda W v + e.$$

In both models, the error term *e* is the traditional normal Gaussian error with constant variance, W is a normalized $n \times n$ weight matrix that identifies the spatial relationships, and X is the n x k data matrix of explanatory variables. The spatial relationships in W are determined by the first-order contiguity of land and water boundaries, and these relationships are indicated with non-zeroes in the off-diagonal elements and are row-stochastic.[22] While determining between Equations (2) and (3) is in practice an empirical question, intuitively, the spatial error model seems more appealing in our dataset. In SEM, there is unobserved heterogeneity that exhibits a spatial pattern, rather than there being actual dependence across observations in the vegetation index as you would have in SAR. That is, there is no actual causal mechanism between the growth of vegetation on one plot of land and production on nearby plots of land. Instead, the mechanisms is likely less direct: due to the mobility and cohesiveness of water, when it is available on one plot of land, its availability is likely increased on nearby plots of land as well, either on the surface or the ground. This in turn will favor the production of crops on nearby plots of land and produce spatial correlation in the NDVI values of the acequias.

To distinguish between the SEM and SAR models, we employ the Lagrange Multiplier (LM) tests on the residuals of an OLS regression, as described in Kim et al. (2003). The LM-Error diagnostic is rejected at the 90 percent confidence level for NDVI, and is not rejected in the LM-Lag, suggesting that the appropriate model is the spatial error model[23]. If there is no misspecification, the only difference between SEM and OLS should lie in the standard errors. To test if observed differences between SEM and OLS coefficient estimates are statistically significant, which would suggest misspecification, the spatial Hausman test is also employed (Pace and LeSage 2008). The results of the spatial Hausman test, reported in the last row of Table 4.6, indicate that the observed differences in the correlation coefficients are not statistically significant.

The final column of Table 4.6 presents the spatial error model estimates for NDVI, which reveals that the spatial autocorrelation had considerable effects on the standard errors, as several variables change in statistical significance. Land fragmentation and extent of urbanization lose their significance, while the availability of groundwater, having a water agreement, and the size of the Acequia gain statistical significance. The interpretation of SEM coefficient estimates is

[22] In place of the first order spatial weight matrix, we also estimated models with "nearest neighbor" weight matrices based on centroids. Qualitatively the results were very similar, but there was a lower model fit in those SEM regression and less intuitive appeal for modeling a irrigation system.
[23] The robust versions of the LM test (Anselin et al. 1996) provided the same result, so they are not listed.

undertaken in the same manner as OLS, so that a coefficient represents the change in the dependent variable from a one unit change in the corresponding independent variable.

To check the robustness of the results, rather than using a time-averaged dependent variable for the units, we repeated this procedure for three selected years. First, 2008 is estimated as it is the most recent year of the data, to detect if the result is driven by historical matters that may or may not still be relevant. Secondly, we test the model over the index from 2000, which is interesting because it is one of several years in the data when a particularly severe drought occurred. Finally, we estimate it in 1985, the oldest data point in the series. The results of these regressions are reported in Table 4.7. An interesting result is that the variables do not seem to change in significance or importance over time.

The only difference in the diagnostics on Table 4.7 from Table 4.6 is that in the drought year regression, 2000, the spatial Hausman test rejects the null hypothesis that the OLS and SEM coefficient estimates are equal at the 90 percent confidence level, which suggests model misspecification. Nevertheless, the model estimates are qualitatively similar to the rest.

To gain more insight into the analytical significance of the coefficients in Tables 4.5 and 4.6, we turn to a set of calculations presented in Table 4.8. In Table 4.8, we have calculated the marginal effect of a one standard deviation increase in the independent variable both in absolute terms, and as a percentage of a standard deviation of the dependent variable[24].

For example, the coefficient estimate on Acequia size in Table 4.6 is -0.032, the standard deviation of Acequia size is 0.515, so the marginal effect is -0.016 (-0.032×0.515). This change represents 20.1 percent of the dependent variable's standard deviation (-0.016/0.081).[25] Table 4.8 reveals that having a water agreement is clearly important in terms of qualitative significance, as it increases the vegetation index by more than half its standard deviation in all estimates. All the variables, statistically significant or not, have non-trivial analytical significance. For instance, while the proportion of the acequia's land that was urbanized was not statistically significant in any specification, a one standard deviation increase in this proportion reduced the vegetation index by about 20 percent of a standard deviation.

[24]Except in the case of the effect of having a water agreement, for which we only use the effect of going from zero to one, as it is an indicator variable.

[25] The reported calculations were done in a spreadsheet with a higher degree of precision, so there is some differences reported due to rounding if a reader were to use the observed values in this chapter.

	2008				2000				1985			
	OLS		SEM		OLS		SEM		OLS		SEM	
Constant	0.317	***	0.303	***	-0.040		-0.048		0.414	***	0.401	***
	(0.034)		(0.031)		(0.034)		(0.031)		(0.034)		(0.031)	
Acequia size	-0.021		-0.035	*	-0.020		-0.040	**	-0.017		-0.032	*
	(0.023)		(0.019)		(0.023)		(0.019)		(0.022)		(0.019)	
Land fragmentation	-0.023	**	-0.016	*	-0.021	*	-0.012		-0.026	**	-0.021	**
	(0.011)		(0.010)		(0.011)		(0.010)		(0.011)		(0.010)	
Urbanization	-0.052	*	-0.048		-0.037		-0.045		-0.042		-0.042	
	(0.030)		(0.032)		(0.030)		(0.032)		(0.030)		(0.032)	
Groundwater availability	0.041		0.057	**	0.025		0.036		0.034		0.053	**
	(0.029)		(0.026)		(0.029)		(0.025)		(0.029)		(0.026)	
Water agreement	0.029		0.049	**	0.029		0.046	**	0.031		0.051	**
	(0.023)		(0.021)		(0.023)		(0.021)		(0.023)		(0.021)	
Hydric soils	0.014	***	0.012	***	0.011	**	0.010	**	0.008		0.006	
	(0.005)		(0.004)		(0.005)		(0.004)		(0.005)		(0.004)	
λ			0.376	**			0.409	**			0.350	*
			(0.186)				(0.180)				(0.190)	
Sample Size	51		51		51		51		51		51	
R^2	0.492		0.550		0.373		0.461		0.372		0.436	
JB	1.707				0.518				4.876			
KB	1.473				1.770				7.521			
LM-Lag	1.275				2.130				0.318			
LM-Error	3.563	*			4.060	**			2.820	*		
S-H Test	6.819				11.571	*			8.209			

Notes: Abreviations: Jarque-Bera test for normality of dependent variable (JB), Koenker-Bassett test for heteroskedasticity (KB), Langrange Multiplier (LM), Spatial Hausman Test (S-H).

Statistical significance indicated at the .01, .05, and .10 level by ***, **, and *, respecitvely.

Table 4.7: Sensitivity analysis

		All Years		2008		2000		1985	
Variable (x_k)	Δx_k	$\beta_k \Delta x_k$	$(\beta_k \Delta x_k)/\sigma_y$	$\beta_k \Delta x_k$	$(\beta_k \Delta x_k)/\sigma_y$	$\beta_k \Delta x_k$	$(\beta_k \Delta x_k)/\sigma_y$	$\beta_k \Delta x_k$	$(\beta_k \Delta x_k)/\sigma_y$
Acequia size	0.515	-0.016	-20.1%	-0.018	-21.8%	-0.021	-27.8%	-0.017	-22.6%
Land fragmentation	0.896	-0.014	-17.8%	-0.015	-17.8%	-0.011	-14.4%	-0.019	-25.6%
Urbanization	0.324	-0.017	-20.7%	-0.015	-18.8%	-0.015	-19.7%	-0.014	-18.7%
Groundwater availability	0.417	0.024	29.9%	0.024	29.1%	0.015	20.1%	0.022	30.1%
Water agreement	1.000	0.045	55.9%	0.049	59.2%	0.046	61.5%	0.051	69.2%
Hydric soils	2.576	0.029	36.2%	0.032	38.5%	0.025	33.4%	0.016	21.9%

Notes: Δx_k is the change in the independent variable, which is one standard deviation for the continuous variables and a unit change for the water sharing agreement dummy. The corresponding correlation coefficient β_k is from the SEM results in Tables 4.6 and 4.7. The standard deviation of the dependent variable is σ_y.

Table 4.8: Analytical significance of marginal effects

Based on the statistical evidence, each of the hypotheses seems reasonably well supported. As already mentioned, smaller acequias performed better over time than larger acequias (H1). The acequias are vulnerable to the fragmentation of land rights (H2) and urbanization (H3), as a standard deviation in each, respectively, reduces the vegetation index by about 20 percent of a standard deviation. Certain properties do make the acequias more robust to droughts by increasing access to alternative sources of water during them, either through groundwater sources (H4), or water sharing agreements (H5). Our results in Table 4.8 indicate that having a water agreement has a marginal effect equivalent to that of a two to three standard deviation increase in groundwater availability. Finally, soil properties associated with water availability and retention increase vegetative production (H6). In absolute value, the magnitude for these hydric soils had the largest marginal effect among the continuous variables.

4.8 Conclusions

This chapter contributes to the research programs on CPR management and on robustness and resilience in SESs. It illustrates that in order to analyze social systems, one often has to understand the environmental factors they interact with, and vice versa. It also demonstrates the mix of technologies and scientific methodologies available, and in this case required, in order to conduct such an analysis. This mix of methods was enabled by the production of a unique dataset and the availability of both social and biophysical data on a common study area. As a result of this interdisciplinary approach, we were able to test several important hypotheses that relate to the sustainability of social-ecological systems.

These hypotheses were largely confirmed. Both water sharing agreements and access to groundwater provide alternative sources to water that help the acequias maintain irrigation practices and produce crops in spite of periodic droughts. Additionally, particular soil properties associated with water retention help the acequias to produce crops in a dry environment. Smaller acequias are better able to maintain crop production per unit area than larger acequias, with a plausible mechanism for this being their lower transaction costs involved in monitoring and enforcements their internal agreements.

While the acequias have been responding to droughts for centuries and seem well-adapted to them, the novel disturbances of land right fragmentation and urbanization appear to be much more difficult for them to resolve. The acequias that have been more exposed to them are producing fewer crops per unit area than other acequias in the valley. In many areas around the world, increasing economic connectivity that these disturbances represent is impinging on the historical practices of community-based management regimes. Such connectivity may afford new opportunities, but we should not be surprised that it can come at a cost. In this case the cost—as revealed by in-person interviews with farmers in the valley—has involved decreased interdependence and solidarity both within and between acequias, as they are less involved in historic traditions and rituals, and more involved in the larger and more developed economy through wage-earning jobs and food markets.

Chapter 5: A New Basin of Attraction and Some Conclusions

Introduction

This chapter is divided into two basic parts: sections 5.1 and 5.2, and the remainder of the chapter. Section 5.1 describes important recent changes that have occurred in Taos valley, particularly in the last fifty years, that have fundamentally altered the basin of attraction described in chapter 2. These changes have resulted from novel disturbances, several of which are statistically analyzed in chapter 4. Section 5.2 discusses the new basin of attraction that has resulted from these novel disturbances. The last part of this chapter consists of the remaining sections, where the implications of these changes for the acequias and systems like them are discussed, and more general conclusions are drawn from the analysis in this chapter and the previous chapters.

Section 5.3 discusses some practical implications that these changes have for the acequias and systems like them. Section 5.4 discusses the theoretical implications of such a multi-disturbance perspective on the analysis and management of robustness and resilience of social-ecological systems. Section 5.5 offers some conclusions regarding community-based CPR management, and includes several suggestions as to what directions this research program might usefully take in the future. Section 5.6 discusses the issue of theoretical generalizability in the context of the diagnostic approach to analysis used primarily in chapter 2, and section 5.7 concludes the dissertation with a brief discussion of policymaking and policy analysis in common-pool resource settings.

5.1 Novel disturbances leading to a New basin of attraction

Several novel disturbances have affected the Taos valley acequias during the last 50 years, some of which have previously been analyzed in chapters 3 and 4. This section will describe the incidence of these disturbances upon the acequias in Taos valley. While these disturbances are not entirely distinguishable from each other and are interconnected, it is useful to list them as follows:

1. The *Abeyta* water rights adjudication
2. Water markets
3. Urbanization
4. Property rights fragmentation
5. Population growth and demographic changes
6. Labor markets

5.1.1. The *Abeyta* adjudication

Approaching and following New Mexico's entrance into statehood in 1912, the state government took an increasingly centralized role with respect to water management. The 1907 water code mandated that the state government actively manage all of the surface water within its borders. In the modern era, the state government seems to have at times played both a positive and a negative role with respect to the acequias. Its doctrine of prior appropriation gives the acequias senior water rights over all other users except for Native Americans. Additionally, several laws recently passed by the state legislature have been extremely favorable to the acequias.[26] There are, however, two state-initiated processes that have disturbed them. The first is the process of adjudicating water rights, and the second is the facilitation of water markets.

Beginning in 1969, the state government of New Mexico took a much more active role in water use in Taos valley, in the form of a court adjudication of water rights for the entire area. Such adjudications are one of the central mandates of the OSE to actively manage and monitor the use of water within the state. As the OSE's website (OSE 2009a) states:

> *Adjudications determine who owns what water rights and in what amount. They are required by statute. The purpose of adjudication is to obtain a judicial determination and definition of water rights within each stream system or underground basin so that the State Engineer may effectively perform water rights administration and meet New Mexico's interstate stream obligations.*

While this certainly can be considered to be a disturbance to the acequias in Taos valley, its effects are somewhat independent of the other changes that are currently taking place. As described by Rivera (1998), the outcome of the case, while lagging several decades and requiring the labor and time of several acequia community leaders, appears to be favorable to the acequias.

5.1.2. Water markets, urbanization and land rights fragmentation

The second process that has been implemented by the state government is the legalization of water markets, through which water rights can be bought and sold and, importantly, separated from the land traditionally associated with them. Water transfers facilitated by legal water markets are a major threat to the traditional functioning of the acequias. In accordance with the more centralized role it has taken, the government of New Mexico currently requires anyone who wants to use water to apply for a permit from the Office of the State Engineer (OSE). This application process includes the possibility of transferring water rights from existing users to new users.

The transaction costs involved in such transfers seems to have been comparably low in New Mexico: "New Mexico transfer applications are processed more quickly by the state engineer, involve fewer protests, and involve significantly lower costs in terms of attorneys' fees and consultants' expenses paid by transfer applications than application in neighboring southwestern states" (NRC 1992, 171). Unfortunately, there are no data available that can reveal the extent to which these transfers have affected the acequias in Taos or elsewhere, but anecdotal evidence from interviews indicates that the effects have been and will be increasingly significant.

There are two basic ways that water transfers can occur that affect acequias: 1) transfer of a water right out of an acequia for a non-irrigation use, and 2) transfer of a water right to a new member of an acequia. Each has its complications, but the former is probably more threatening,

[26] Two laws passed since 2003 have enabled to the acequias to require consent of the members before a water right is transferred to a non-member, and to bank water for future use by members. These laws have not gone unchallenged, but as of this writing remain in force.

since it involves the semi-permanent removal of water rights from an acequia. One problem produced by the intra-acequia transfers is the lack of understanding of traditional acequia rules and customs that newcomers frequently bring with them. It also increases the number of members of each acequia over time, complicating collective-action among members. Water rights transferred from traditional irrigation uses may be severed from the land appurtenant to the river, which facilitates the use of such transfers for non-irrigation purposes. Buyers in these cases are typically municipalities and real estate development interests.

As discussed in chapter 4, two disturbances that are closely related to these market transfers are urbanization and land right fragmentation. Each of these occurs in large part through the transfer of water rights either within acequias or out of acequias entirely and to the municipality of Taos. Urbanization also includes physical alterations of the land and disruptions of historical hydrological processes. Chapter 4 makes it clear that each of these disturbances has had deleterious effects on the acequias in Taos.

5.1.3. Population growth and demographic changes

Pressure on acequia members to sell their water rights in water markets would not occur if it were not for rapid population growth in Taos, which is a trend that is occurring throughout New Mexico. Two basic trends have typified the demographic changes occurring in Taos valley: in-migration of newcomers and out-migration of youths. In-migration has outweighed ex-migration, leading to steady increases in population over time. Table 5.1 shows several demographic trends over time in Taos County, starting with its population from 1900 to 2000 according to the U.S. Decadal Census. Each year shows an increase, except for 1950 and 1960, in which the population decreased. This seems to reflect a large exodus, primarily caused by World War II, when many young men either enlisted or otherwise left to help the war effort. Several interviewees commented that they saw this as an important and irreversible shift, or perhaps the first major sign of a trend where children of lifelong farmers left the valley to explore other opportunities. This trend continues today.

Year	Population	Median Age	Median household income	Per Capita Income	Hispanic	Percent Hispanic
1900	10889	-	-	-	-	-
1910	12008	-	-	-	-	-
1920	12773	-	-	-	-	-
1930	14394	-	-	-	-	-
1940	18528	-	-	-	-	-
1950	17146	19.2	-	-	-	-
1960	15934	19.6	-	-	-	-
1970	17516	23.3	-	$1,717	-	-
1980	19456	28.3	$10,717	$4,613	13448	69%
1990	23118	33.9	$16,966	$9,158	15190	66%
2000	29,979	39.5	$26,762	$16,103	17388	58%

Table 5.1: Taos County historical demographic information (Sources: BBER 2009; USCB 2009).

An additional trend that is displayed by Table 5.1 is the increase in age of the county's residents over time. This results in large part from the out-migration just mentioned, where younger members of the communities whose parents used to farm often leave, and are replaced by older residents who have the wealth that frequently comes with age to retire or purchase a second home in Taos valley. This highlights another shift: an increase in average wealth in the valley, shown by the next two columns. This transition has also involved a shift in the ethnic makeup of the area, with whites becoming more prevalent and Hispanics less so, which is shown in the final column. This has increased the ethnic diversity of the acequias, which traditionally were entirely, or almost entirely, Hispanic.

5.1.4. Recent economic development and new jobs

The population growth in Taos County has largely centered in Taos valley, particularly its urban centers. This new growth has created a demand not only for scarce water supplies, but also for labor. The acequia members are now almost entirely integrated into local and regional labor markets, earning their living through full or part-time employment rather than by being farmers or ranchers. Table 5.2 shows the sectoral distribution of employment in Taos County in 2000. Only 4.4% of respondents stated that they were in the sector that included agriculture. Meanwhile, there is a trend in the first several categories towards activities associated with tourism, real estate, and entertainment.

INDUSTRY	Total	%
Educational, health and social services	2,753	20.3
Arts, entertainment, recreation, accommodation and food services	2,595	19.1
Retail trade	1,732	12.8
Construction	1,367	10.1
Professional, scientific, management, administrative, and waste management services	933	6.9
Public administration	884	6.5
Finance, insurance, real estate, and rental and leasing	729	5.4
Other services (except public administration)	702	5.2
Agriculture, forestry, fishing and hunting, and mining	593	4.4
Manufacturing	435	3.2
Transportation and warehousing, and utilities	413	3
Wholesale trade	222	1.6
Information	198	1.5

Table 5.2: Distribution of employment in Taos by sector in 2000 (source: USCB 2009)

5.2 A new basin of attraction

Figure 2.6 in chapter 2 displays the conditions that have held historically for the acequias in Taos valley. As a result of the disturbances just discussed, the modern situation is quite different, and is illustrated on figure 5.1. In contrast with figure 2.6, figure 5.1 includes several new components which have disturbed the traditional system. This situation can be described as a flip to an alternative basin of attraction, leading to the interpretation that the acequias are vulnerable to the suite of novel disturbances, based on the definition of resilience discussed in chapter 1. The state variables whose values have changed are listed in table 5.3.

Variable	Direction
Resource dependence	Lower
Collective action	Lower
Leadership	Lower
User and resource boundaries	Lower
Parcel sizes	Smaller
User group size	Larger
Cultural heterogeneity	Higher
Common property pastures	Absent
Livestock production	Absent
Crop production	Slightly lower

Table 5.3: Changes in the values of important state variables

5.2.1 Lower resource dependence, collective action, and leadership

The acequia members' level of dependence on water has fallen dramatically to the point where essentially none of the farmers rely on the traditional system of farming and ranching in order to support themselves. Of the 42 acequia officials interviewed, not a single one relied on farming or ranching for a living. Several even reported farming at a loss, where their primary motivation to continue was to maintain their culture. Because few to none of the members and officers farm for a living, the water they use to irrigate has little economic necessity. Several interviewers reported that when there is no water, they simply do not irrigate, because there is no necessity to do so. This situation stands in stark contrast to the extraordinarily high level of dependence that existed in the historical basin of attraction, where water was a vital resource needed to sustain livelihoods of entire communities. This lower dependence has led to and co-developed with several other processes.

The availability of jobs in Taos and elsewhere has drastically altered the incentives involved in producing the important public goods discussed in chapter 2, particularly for the acequia officers, who are responsible for the majority of those public goods. Collective action as a variable was not directly measured over time, but interviewees were unanimous in their accounts of the declining levels of collective action in their acequias. Common examples included consistently low attendance at annual meetings and low attendance at annual ditch cleanings, and general concerns about members who no longer irrigated their fields[27].

Additionally, the acequia officers interviewed frequently commented that it had become difficult to find members to take their place, and that the positions had become much less desirable. The interviewees (primarily officers) were mostly past middle age, frequently retired from full-time jobs, and commonly reported having been in their positions for extended periods of time, since they could not find members to take the positions from them in annual or biennial elections. According to the U.S. Census Bureau, the average age of farm operators in Taos County was 58.7

[27] This is a concern in many of the acequias because of a law stating that if water rights are unused for a period of five years, they are forfeited.

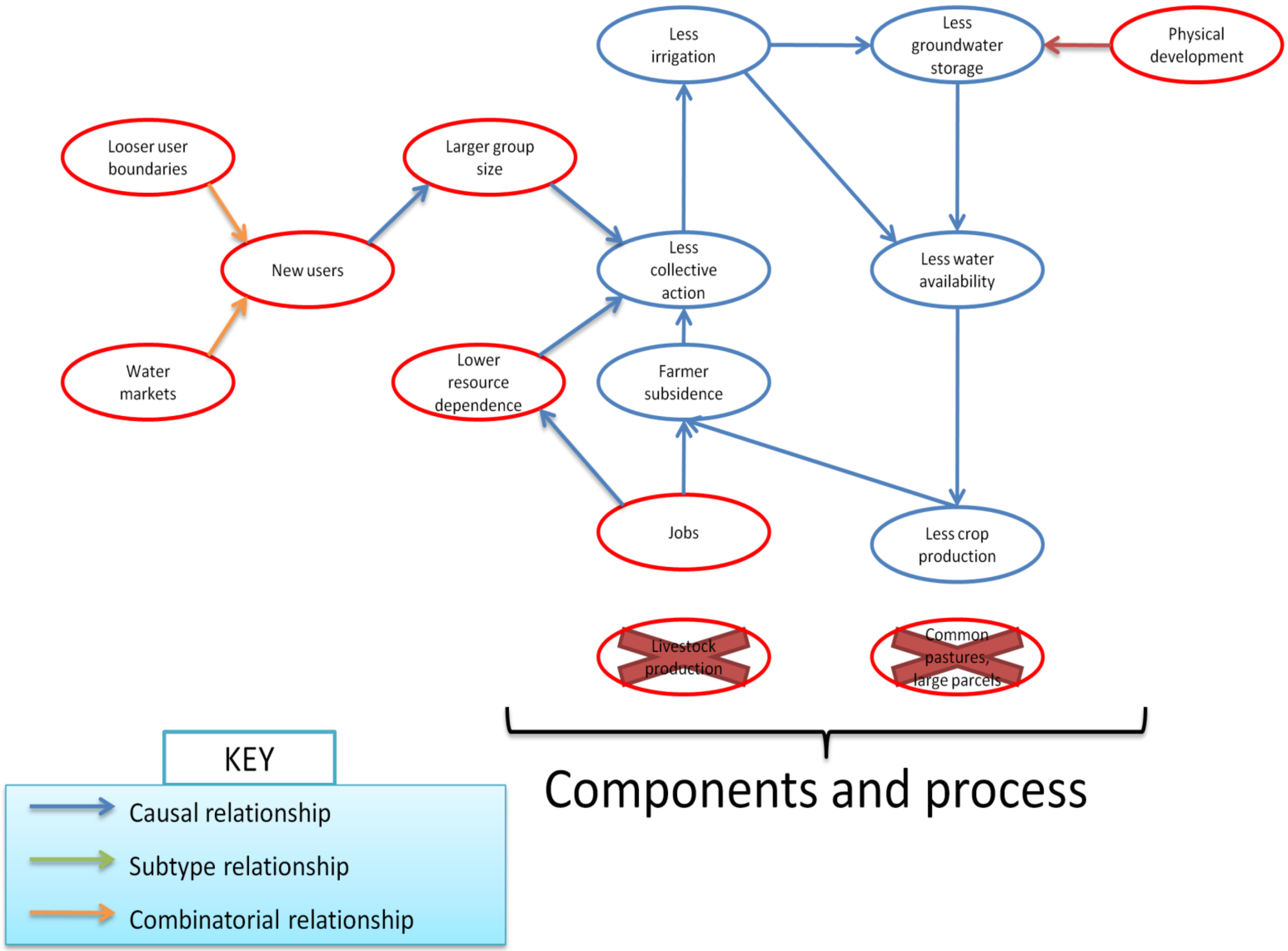

Figure 5.1: New disturbances and basin of attraction

in 2002 and 59.4 in 2007 (USCB 2009). This has made it more difficult for the acequias to obtain the historical levels of leadership they once benefited from, which was critical to the supply of public goods needed to maintain the systems and historical levels of collective action.

5.2.2 Boundaries, parcel and group size, and heterogeneity

Largely through water market transfers from traditional irrigators to new users, the user group boundaries seem to have declined, although they still do exist and it is not correct to label the regime open-access. Mayordomos and commissioners still play active roles in maintaining these boundaries, but have had to contend with these new users.

The boundaries are now less clear for two reasons: first, the water markets do not seem to be very transparent to the acequias themselves, or seemingly to anyone in the valley, making it more difficult to determine who does and who does not have rights to surface water. Perhaps the more important mechanism that has made it difficult to maintain these boundaries is the availability of modern technology to tap groundwater through domestic wells. This is a problem because of the strong surface-groundwater connection in the valley, meaning that withdrawals from one resource are also withdrawals from the other. If the acequias cannot effectively limit domestic groundwater consumption in the valley, their user boundaries are threatened.

Related to the user group boundaries, the user group sizes, or number of members in each acequia, appear to be increasing. This is reflected by the land right subdivisions previously discussed. This in turn has led to an increase in ethnic and cultural heterogeneity among the users groups, which has at times caused difficulties in arriving at common understandings regarding water and land use among old and new users. The most frequently mentioned example of this problem involves the easement rights that acequia members have along the main canal as it travels through individuals’ private parcels of land. Frequently newcomers do not recognize this right, and view the members cleaning the main ditch as an infringement on their private property rights.

Finally, the private parcels of land have decreased in size, for what appears to be two main reasons. The first is the addition of new landowners into the valley, and the second is intergenerational transfers between existing acequia users. In part because of the decline in resource dependence, these transfers have apparently been accompanied by new smaller plots of land, which often fall into disuse. There are few incentives for the younger generation to maintain parcel sizes adequate for farming by consolidating several inherited parcels, and they appear to frequently use their smaller parcels for non-agricultural purposes, such as building a house.

5.2.3 Livestock production and common pastures

The livestock variable that was crucial for economic self-reliance in the historical basin of attraction is now essentially gone, as is the communal grazing land that apparently once existed. Interviewees reported that ranching has all but disappeared from the valley. This was confirmed by extensive informal ground-truthing that was a necessary part of the fieldwork; there are several ranches still present, but it is safe to say that ranching as an economically significant activity has all but disappeared from Taos valley. Figure 5.2 shows a decline in the number of cattle in Taos County, and a precipitous decline in the number of sheep. Several acequia farmers indicated that sheep had historically been the primary grazing animal in the valley. As of 2008, only 700 were reported in the county, as contrasted with 17,000 in 1975.

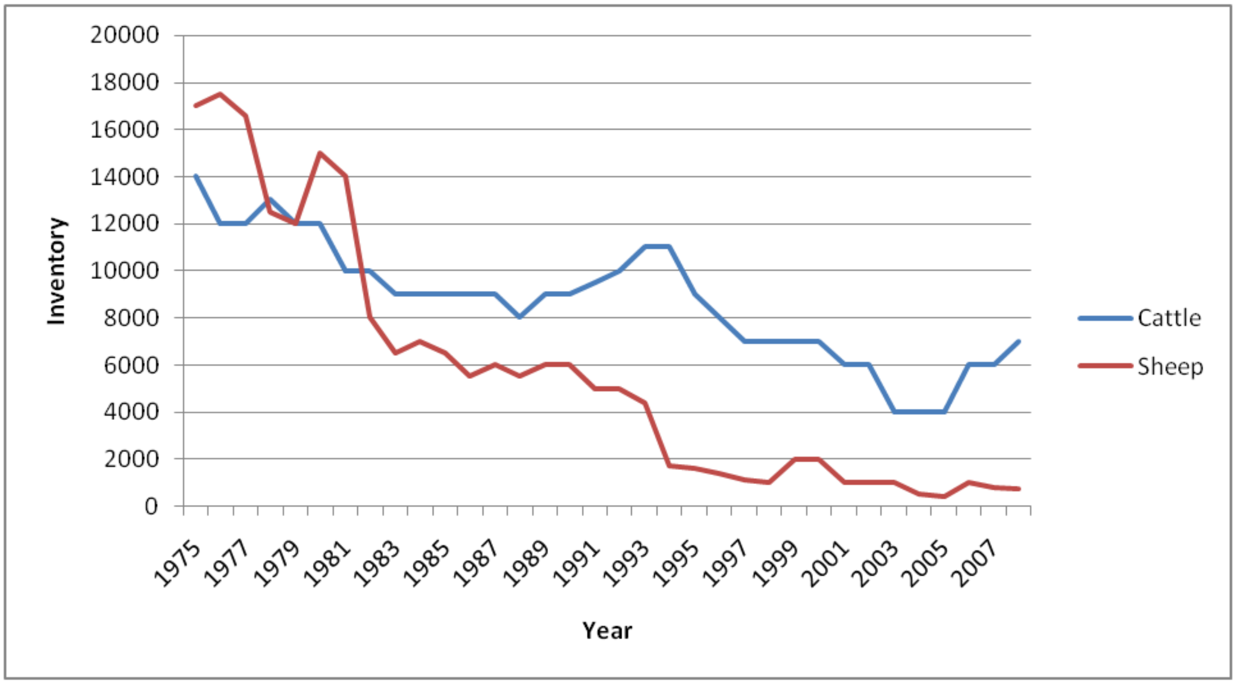

Figure 5.2: Over time trends in livestock levels in Taos County (Source: USDA NASS 2009).

This declination is related to several of the disturbances just discussed. First, in an arid area such as Taos, what is required in order to be economically viable is a plot of land of at least a minimum size, below which grazing animals will degrade marginal lands. There had been an important balance in the historical basin where the animals were kept in common lowlands during the winter, but sent up to high ground in the summer, such as areas of what are now part of Carson National Forest (and managed by the USFS). With the subdivisions of private parcels and absence of common pastures, this system is no longer possible.

This declining trend in sheep production reflects a national trend in the United States, as well as in New Mexico (see figure 5.3). The National Research Council (NRC) (2008, 17-19) mentions several reasons for these trends that are relevant here:

"*Labor loss during World War II.* World War II drew a great deal of labor out of American agriculture on a permanent basis. This shift affected all of agriculture, including the subsequent availability of labor for sheep and lamb production."

"Grazing permits and restrictions. The regulations and permits for grazing on public lands have changed considerably over the last several decades, with impacts on the availability of land for sheep production."

"Competition from other fibers. The advent of synthetic fibers (such as polyester, rayon, and acrylic) in the 1950s and 1960s resulted in a growing substitution of the lower-cost synthetics for wool, and to a lesser extent cotton, in apparel, carpet, and industrial goods."

"Competition from imports. Between 1990 and 2005, imports of lamb, primarily from Australia and New Zealand, grew from 18.60 million kilograms, about 10 percent of domestic lamb supply, to 81.65 million kilograms, nearly equal to U.S. domestic production and half the total domestic supply."

Figure 5.3: United States sheep inventory in millions. Source: NRC 2008

5.2.4 Crop production – NDVI

If crop production in the acequias is declining this is an important indicator of decreased functionality. In chapters 2 and 4, NDVI as an estimate of crop production is a central component of the acequias' performance and persistence over time. Figure 5.4 shows how acequia crop production in Taos valley as estimated by average NDVI values has slightly decreased over time. This does not automatically mean that this has resulted from the factors discussed here, however, in part because of the tight connection between NDVI and streamflow over time established in chapter 2. Additionally, NDVI can be highly sensitive to variations in precipitation in preceding time periods, particularly in arid or semi-arid regions (Ichii et al. 2002; Wang et al. 2003).

Because of the importance of snowmelt in producing streamflow in the Taos area, we can also expect a tight relationship between precipitation in months leading up to the growing season, particularly winter months, and streamflow during the growing season. This is illustrated and confirmed in figure 5.5, which is a scatterplot between precipitation in the 6 months leading up to the growing season and streamflow in each year. Monthly precipitation values were taken from a weather station in Taos valley maintained by the National Climatic Data Center, and streamflows were taken from USGS gauge data. Finally, figure 5.6 shows that this 6 month precipitation value has been decreasing over time, which might explain the linear trend displayed in figure 5.4.

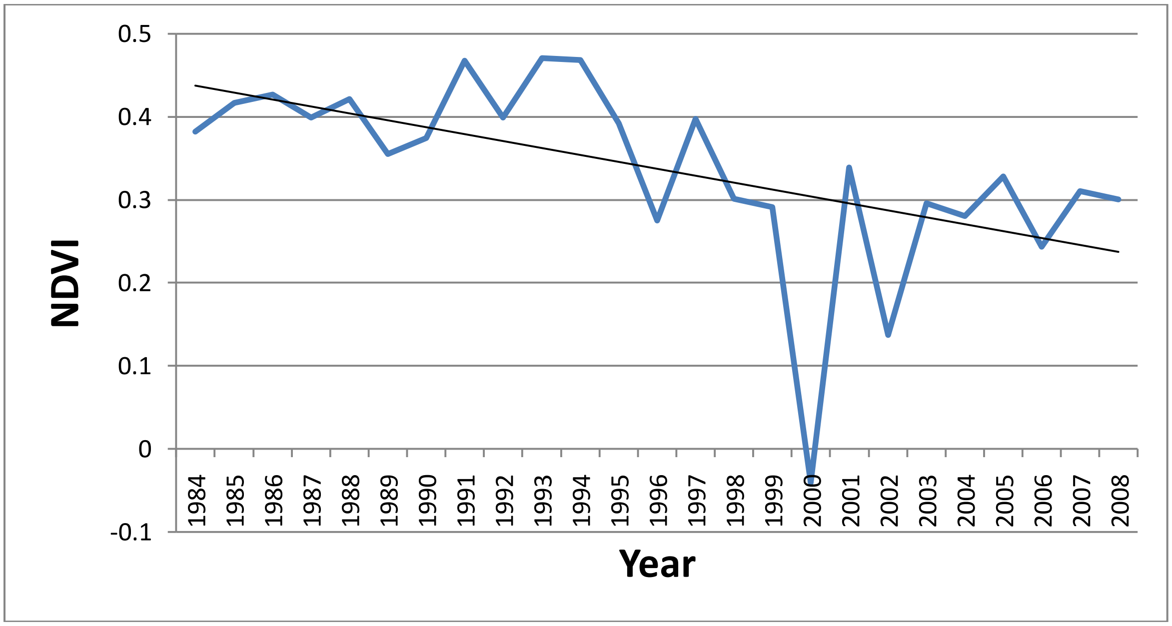

Figure 5.4: NDVI over time

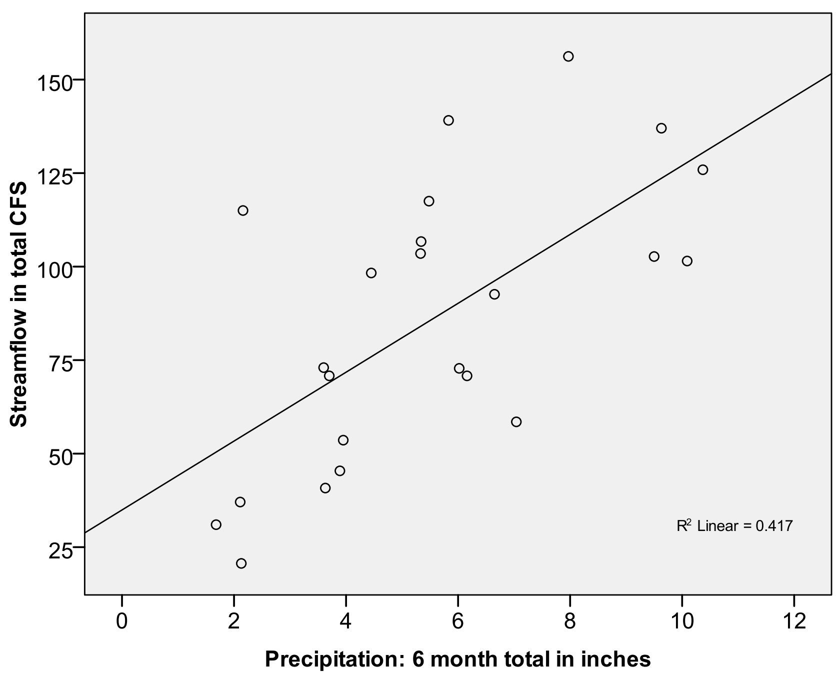

Figure 5.5: Scatterplot between precipitation and streamflow

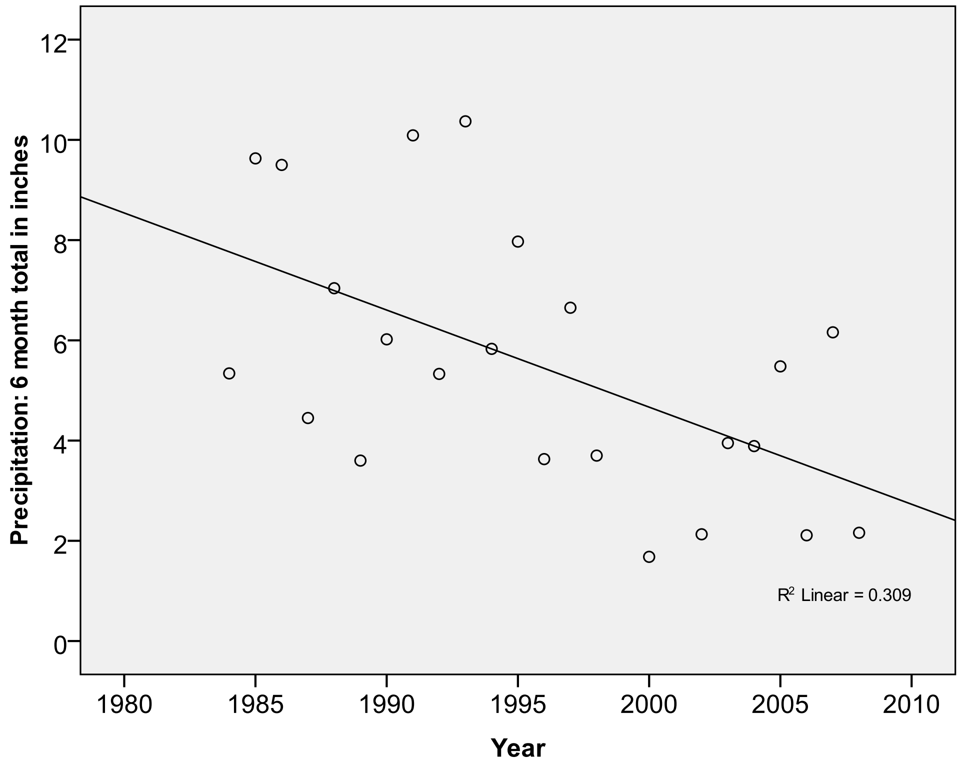

Figure 5.6: Scatterplot between year and 6 month precipitation total

To account for the possibility that declining NDVI over time could simply be a function of declining streamflow or precipitation over the same period of time, several time series regressions were run using various different variables for precipitation (total precipitation for the period 1 month, 3 months, and 6 months before the date of an image used to produce NDVI values for that year). The model using the 3 month total had fewer problems with multicollinearity and a higher r-squared value than the other models. The model and results are presented below. A lagged version of dependent variable is not included, as temporal autocorrelation is ruled out in the analysis from chapter 2.

$NDVI_y = YEAR_y + CFS_y + Precipitation_y + e$

	Coefficients	**Standard Error**	**t stat**	**P-value**
Intercept	659.280	448.898	1.469	0.158
Year	-0.323	0.224	-1.441	0.166
CFS	0.139	0.046	3.042	0.007
Precipitation	2.149	0.910	2.363	0.029
R-square:	0.694			

Table 5.4: Time series results

Some limitations to this analysis should be mentioned. First, the low number of observations (23 as a result of missing precipitation data for 2 years) means we should only take these results as suggestive. Additionally, because only one weather station was used for this analysis, we cannot be sure that its measurements represent the amount of precipitation received in all of the areas for which NDVI values were measured.

The results show that CFS and Precipitation are both highly significant, while the Year variable is not significant at the 5 or 10% levels. Using the 6-month total for precipitation increases the p-value for the year variable to 0.248, lowers the r-square to 0.682, and introduces multicollinearity, particularly between CFS and Precipitation. As a result of this analysis, we can conclude that, while NDVI as an estimate for agricultural production seems to be slightly declining over the time period analyzed, we cannot infer with much certainty that this is a result of the suite of disturbances described earlier.

5.2.5 Interpreting causes and outcomes

It seems reasonable to argue that the acequias have demonstrated a vulnerability to a suite of novel disturbances through this transition to a new basin of attraction with lower values in key functional variables. The SES framework as applied in chapter 2 provides a reasonably thorough explanation of how the properties of the acequias have enabled them to persist historically by responding to droughts. Arriving at an explanation as to how those historical properties caused them to be vulnerable to novel disturbances is more difficult. Explaining it by referring to the trade-offs that all complex systems experience in their robustness to various disturbances seems plausible, and this will be discussed later in this chapter. However, I do not think that this is a satisfying mechanistic explanation in terms of CPR theory. One interviewee did comment that he thought the acequias' recent vulnerability was due to their relatively decentralized nature, which has inhibited a system-wide response. Because the acequias are somewhat decentralized, when individual acequias or members are threatened by economic development or market transfers, they do not have recourse to other acequias' resources to help them respond. The TVAA, while serving as a legal representative of all of the acequias in the *Abeyta* case, has not historically played a role in helping its members respond to these other disturbances.

Some scholars might even argue that the acequias have not displayed a vulnerability, but have merely transformed themselves into a new system, and thus have exhibited high transformability, defined by Walker et al. (2004) as "the capacity to create a fundamentally new system when ecological, economic, or social (including political) conditions make the existing system untenable."

Following the argument put forward toward the end of chapter 1, that we can infer a change in a basin of attraction from changes in several fundamental state variables, my own interpretation is that acequias have flipped into an alternate basin of attraction. Thus, the acequias can be judged to have been *robust* to historical droughts, but *vulnerable* to novel disturbances of economic development and market penetration into their communities. This vulnerability is demonstrated in two, complementary ways: 1) the loss of livestock and common property grazing lands; 2) a shift in their basin of attraction from a self-sufficient basin to one that is inextricably connected to a larger environment.

5.3 Practical implications

5.3.1 External environments

The transition that the acequias have undergone to a new basin of attraction is largely a function of their increasing connectivity to what was previously an entirely external social and political environment. This increase in connectivity has practical implications for them, and for systems like them, as well as for the larger environment they are now integrated into. For the local systems, this frequently means fundamental disruptions of their social and biophysical structures and identity. While traditional systems like the acequias have adapted well to a historical disturbance regime, this increased connectedness is different from previous disturbances in important ways. First, droughts and floods are periodic, and thus facilitate a sustained robustness and vigilance. As Janssen and Anderies (2007, 51) note: "a challenge regarding decisions to invest in enhancing robustness is the lack of feedback from previous decisions made. Once a society is successful in increasing robustness, a necessary consequence is that fewer undesired impacts are experienced. This leaves citizens wondering about the value or necessity of investment in enhancing robustness."

The periodicity of historical disturbances experienced by traditional irrigation systems like the acequias helps to maintain the required institutional memory that enables their continued robustness to them. In the language of resilience described in the first chapter of this dissertation, the fluctuations of a state variable along its dimension help to maintain the latitude of the basin along that same dimension. If fluctuations are dampened, the stability landscape shrinks and is less resilient along that dimension.

However, an increase in connectedness, which is distinguished from periodic flow disturbances by the typology presented in chapter 3 of this dissertation, is generally not periodic. Instead, it is usually steadily cumulative[28]. There is no quality of "stress and release" that characterizes processes of adaptation in a variety of systems. As such, these new disturbances present a type of challenge to local systems that they have not encountered before. It seems likely that many of them will respond the way the acequias have, which is to fundamentally change their structure and function as a traditional irrigation system in order to integrate themselves into a larger system. Proponents of economic integration and open markets might argue that this transition ultimately leads to more positive outcomes and opportunities for those involved. This point of view was in fact reflected in several of the interviews, where farmers commented on how much easier their lives had become now that their survival was not dependent on agriculture in such a harsh environment.

While this increase in connectivity may help the farmers in these smaller systems by giving them resources and opportunities they otherwise would not have, this process introduces new vulnerabilities. Walker et al. (2009) describe an example of this in the Goulburn-Broken Catchment of Australia, where external energy inputs are now required in order to pump saline groundwater from irrigated areas so that it does not rise too high and threaten agricultural production. Additional inputs of fertilizer and lime are also now required in order to maintain

[28] This is the reasoning behind the inference early in this chapter that steadily declining values in agricultural production and livestock populations are a result of this suite of disturbances.

economic viability of this agricultural system. These additional resources have allowed the farmers to continue their irrigation practices, but have left the ecological system more fragile.

5.3.2 Hysteresis in CPR settings

This chapter has so far described a shift in the acequias' basin of attraction from one of self-reliance towards an integration with a larger political-economic context. It is apparent that this process is occurring in many areas around the world, often in contexts quite different in some ways from that of the acequias (see Gonzalez et al. 2008). This has important implications for both the local systems and for the larger system that is quickly incorporating them. For the local systems, the fundamental shifts that have been described will most likely be difficult to reverse. This condition is frequently referred to as path dependence or hysteresis.

The literature on resilience and basins of attraction emphasizes the difficulty in reversing such shifts (see Scheffer et al. 2001), and it seems likely that the acequias exhibit this property. First, there is the loss of indigenous knowledge that has occurred with the shift to a new basin of attraction, where new generations of farmers are not taught the traditional methods and knowledge that are necessary for effective irrigation in the valley. This knowledge is more easily lost than it can be reacquired. Additionally, the subdivisions of private parcels, discussed earlier, make it extremely difficult to maintain an economically viable grazing system. Commonly owned grazing lands are mostly gone, and a modern property rights system now overlays the acequias' traditional institutional arrangements. Traditional access to upland grazing and forest lands has also been substantially removed. The vast majority of the highlands above Taos valley are now owned by private individuals, the Taos Pueblo, or by the United States Forest Service through the Carson National Forest. Reversing this shift would incur extensive transaction costs and would require overcoming interests vested in the present property rights structure. Marshall (2005) discusses how the transaction costs involved in reserving a shift such as this leads to self-reinforcing *path dependence,* which is a similar concept to hysteresis.

Additionally, physical development of the land, such as paving roads and parking lots is difficult to reverse, and changes the hydrology of the area, increasing surface run-off and decreasing percolation into aquifers that the acequias have historically depended on. This occurs both in the municipal area of Taos, and within traditionally irrigated fields that are being developed by newcomers. This second example has the additional consequence of displacing traditionally valuable agricultural land. Additionally, as land that was once used to produce crops is displaced by other land use types, the traditional soil structure that was maintained by plant roots may be altered in such a way as to inhibit soil water retention and increase run-off (Scheffer et al. 2001). This may make it difficult to replant crops onto these lands, even if they have not been paved over. It thus seems quite unlikely that the acequias in Taos will return to their historical basin of attraction, at least without some drastic or catastrophic challenge to the new basin that forces the system to fundamentally renew and reorganize itself (Gunderson and Holling 2002).

5.4 Theoretical implications for SES theory and management

With respect to SESs and disturbances, the main lesson learned in this dissertation is that being robust or vulnerable are not system properties, but characteristics of the relationship between a system, at a particular level and particular time, and a particular type of disturbance. It is not strictly meaningful or correct to say that the acequias are robust or vulnerable. Instead, the acequias' experiences confirm a central tenant of theories dealing with robustness, resilience, and other concepts such as highly optimized tolerance (HOT). This tenet states that complex systems become vulnerable to one set of disturbances when they adapt to another set (Carlson and Doyle 2002; Janssen et al. 2007). "Complex systems must trade off the capacity to cope with some types of variability to become robust to others" (Janssen et al. 2007, 309).

Unfortunately, characterizing robustness or resilience as a property of a SES is found in parts of the literature, most often when authors speak of the low or high resilience of a particular system (Walker and Salt 2006). This may result in part from the fact that "most published accounts of regime shifts involve a single dominant shift defined by one, often slowly changing, variable in an ecosystem" (Anderies et al. 2006). Multiple dimensions along which a system is robust or vulnerable are under-emphasized.

Recognizing these trade-offs and that robustness or resilience is a relationship between a system and a disturbance and not a property of that system has several implications for their analysis and management in complex SESs. To begin with, improving either is not an optimization problem. Instead, there are trade-offs between robustness and resilience to various types of disturbances, and there is frequently a trade-off between high performance along some metric and the stability of that metric (Janssen and Anderies 2007). The acequias exhibit both of these features. They have proved to be historically robust to droughts, while they are vulnerable to more recent disturbances they have faced. Additionally, while their agricultural production has been robust to droughts over time, they are noted for having generally low levels of productivity when compared to more modern agricultural systems. More recently, they have become involved in local labor markets and their average income has increased. If we consider income to be a performance metric, then they have improved performance; however, this has lowered dependence on the resource and helped to shift the irrigation system from one basin of attraction to another one associated with a new set of relationships and possible vulnerabilities[29].

These trade-offs force users and managers to make difficult decisions because they are uncertain about the future dynamics of the system and the future incidence of different types of disturbances upon it. In a world of uncertainty and multiple equilibria, adaptability becomes more important than maximization or optimality. This is because much of the uncertainty we face is not resolvable into calculable risk, due to the complex and frequently non-linear interactions that characterize complex human and natural systems. As Holling (1995, 14) states:

> *In principle, therefore, there is an inherent unknowability, as well as unpredictability, concerning these evolving, managed ecosystems and the societies with which they are linked. The essential point is that evolving systems require policies and actions that not only satisfy social objectives but, at the same*

[29] Janssen and Anderies (2007) mention this example as well.

time, also achieve continually modified understanding of the evolving conditions and provide flexibility for adaptation to surprises.

These observations have direct implications for SES management and the fields of environmental policy analysis and natural resource management, which at times have attempted to characterize their enterprise as a process of analytical optimization. In economics this optimum takes the form of allocative efficiency or Pareto optimality (Baumol and Oates 1998), while in natural resource management science it has involved single-species population models and the concept of the maximum sustainable yield (Gordon 1954). In the presence of trade-offs and irreducible uncertainties, however, this can be an unproductive and misleading approach.

When attempting to improve the robustness of a SES, I would argue that the best intellectual approach is not to envision some theoretical optimum that we then try to attain. Instead, a comparative approach would likely be more useful, where incremental gains along certain dimensions within a stability landscape can be made with respect to a current situation. We also need to be aware of the trade-offs involved in shifting the state of the system or changing the stability landscape, for increasing latitude along one dimension will likely decrease it along others.

This can be aided by understanding the processes that currently maintain the system in a self-reinforcing basin of attraction. If we can understand the relationships between the system's components and/or state variables, we can understand how it maintains itself in a desirable condition, and what we can do to maintain this condition. We can also predict what changes will cause it to flip into an alternate basin. For example, with knowledge of the historical basin of attraction for the acequias, we could have predicted that a diminution of resource dependence, among other things, would have likely caused a shift to a different basin of attraction.

5.5 Implications for CPR theory and analysis

5.5.1 Traditional theory

This work confirms much of the existing literature on community-based CPR management. Ostrom's (1990) design principles for successful collective-action among CPR users are largely confirmed, based on both the historical and the modern basins of attraction discussed in chapter 2 and in this chapter. Historically, when there were high levels of collective-action in the acequias, each of the principles were either moderately or strongly present, as listed in table 2.5 in chapter 2. Currently, interviewees have reported sharp declines in levels of collective-action, and several of these principles have been substantially weakened.

In addition to confirming Ostrom's institutional design principles, the acequias confirm theories regarding the properties of user groups that maintain successful collective-action for CPR management. According to the statistical analysis in chapter 4, small-to-medium sized groups perform better over time than larger groups (Olson 1965; Ostrom et al. 1994). Heterogeneity has various effects, depending on how it is operationalized. Historically, when high levels of collective-action were obtained, the acequias had low ethnic and cultural heterogeneity, but high heterogeneity with respect to property rights. Additionally, leadership roles associated with this high level of property rights heterogeneity proved extremely important in providing public goods and sustaining collective action.

Finally, there are two other factors that have been slightly less well established in the CPR literature that are extremely important in this study: 1) resource dependence and 2) the external environment. As discussed in the first half of this chapter, a lowering of resource dependence is a key change between the old basin of attraction and the new one. This in turn is a result of an increase in connectivity between the acequias and an expanding social-economic environment that has supplied them access to full-time jobs, so that they no longer need to irrigate and farm in order to sustain themselves. With this diminution in resource dependence, the incentives for the acequias members to incur costs in order to maintain cooperation and collective action have decreased, causing less collective action to take place.

I believe that these changes confirm a particular interpretation of Ostrom's (1990) design principles, and other factors associated with sustaining collective-action in CPR settings. This interpretation is that they do not represent a simple additive theory of robust institutional design. Such an approach would unconditionally prescribe the application of each of the principles, one after another, to any CPR setting, and would assume that with the addition of each principle, the chances for successful collective-action are improved. Likewise, such an approach would assume that the removal of one or two principles would not drastically reduce collective-action in a given setting if the remaining principles were still present.

The relationship between each of these principles and sustainable collective-action, however, is non-additive, or configural. Several of the principles are still present in the modern basin, where much lower levels of collective-action are found. However, key elements of the historical basin are missing, and this drastically lowers the effectiveness of the remaining principles and other properties of the acequias in sustaining collective-action. This observation is not limited to design principles. Looking at the acequias in Taos, one might conclude that irrigation ditches in such systems should go unlined as a matter of principle in order to recharge local shallow aquifers and ameliorate upstream-downstream collective-action problems. However, the importance of water seepage depends critically on where exactly the water goes once it has left the surface layer. In many circumstances, it may be lost to the local or regional system entirely. This is a large concern of government officials in New Mexico involved in acequia infrastructure-improvement projects when they determine whether or not to help an acequia pay to have its ditches lined in order to improve its conductive efficiency. As such, I would argue that a diagnostic approach, where the relevance and importance of any particular variable in the system is a function of the presence and values of other variables, is very important to take when analyzing SESs.

5.5.2 Expanding theory

There are three ways in which this dissertation expands on the existing CPR management literature by studying the acequias: the first is to examine important biophysical properties and how they affect outcomes. The second is to complement the social analysis with a structural network perspective. The third is to explore the incidence of various types of disturbances on the acequias, primarily resulting from their interactions with their external political and economic environment.

Historically, the CPR management literature has focused primarily on social/institutional factors, limiting biophysical analysis to relatively simple typologies that explore the social implications of the nature of the good emerging from the resource system. However, this dissertation illustrates that without reasonably good knowledge of the biophysical system, we cannot understand the social system it interacts with, or how the two combine to form a resilient or vulnerable system. The most important biophysical component for the acequias in Taos is the strong connection between surface water and groundwater in the valley, and more generally how the hydrology, geology, and pedology of the area increase water availability in a water-scarce environment. The importance of this is discussed in chapter 2, and statistically tested in chapter 4. Without some understanding of these biophysical features, we would not understand completely how the system has survived over a long period of time through a mix of social and biophysical properties.

In addition to moving towards greater biophysical sophistication, this work augments the discussion of the social system with analysis inspired by network theory. Chapter 2 describes in qualitative terms how the structure of the network the acequias compose helps them to economize on transaction costs and to respond to droughts. Chapter 4 confirms that bridging links between acequias in this network help those involved maintain agricultural production over time.

The inspiration for the hypotheses regarding the network properties discussed in chapter 2 is drawn primarily from analyses of non-human networks (Barabasi 2002; Han et al. 2004; Olesen et al. 2007; Webb and Bodin 2008). Although this study conducts a qualitative instead of a quantitative network analysis, it does confirm the association of the joint network properties of centrality and modularity with robustness that has typified much of this literature[30].

Unfortunately, this analysis also illustrates the difficulties involved in applying a network analysis to a SES, because in fact no such formal analysis was conducted. There are several favors that contribute to this difficulty. To begin with, it is not at all clear in a SES what the nodes or links should be, given that such systems involve human and non-human components and relationships between them (Janssen et al. 2006). Without carefully addressing this problem, calculating the properties of a network in a SES could be a rather meaningless exercise. One possible solution that has been empirically applied is to conduct social network analyses of the communities that manage natural resources (Bodin and Norberg 2005). This still leaves several problems to be addressed.

First, social systems are *heterarchies*, where multiple types of links occur among the same set of nodes. Traditional social network analyses have tended to analyze situations where only one

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[30] In the quantitative network literature, centrality is related to the extent to which the degree distribution is scale-free, and the actual mechanism for robustness is that properties protect against the random removal of a node, most of which are not highly centralized in such networks. It is unclear to what extent this same mechanism has served the acequias. The discussion in chapter 2 describes the importance of these properties primarily as economizing on transaction costs involved in sustaining collective action.

type of link occurs or is the most important among the specified set of actors. However, in SESs, there are a variety of ways in which participants relate to each other and to the resource. A formal calculation of statistical properties of one of these types of links could be very misleading if there are several other types of links that are important and which interact with the analyzed link or relationship. The second difficulty in conducting such analyses of a SES is related to the first: because of the multiple types of links that may be relevant in a SES, the amount of data collection required is greatly expanded, probably beyond the resources available to many projects.

The third way in which this analysis expands on previous work is by exploring several different types of disturbances that the acequias have confronted. The implications of multiple types of disturbances and the trade-offs involved for a system in becoming robust or resilient to any of them have already been discussed. With the exception of droughts, each one of these disturbances is a result of an increase in connectivity between the acequias and their external political/economic environment.

The practical implications for the acequias of this increase in connectivity have already been discussed. In addition, this increase in connectivity has implications for future scholarly work on community-based CPR management. Historically, much of this work has focused primarily on the important properties of the communities themselves, and not their larger social, political, or biophysical context (Agrawal 2003). With these external environments imposing themselves more and more on local systems, we will have to consider the attributes of these environments, and how they interact with more local settings to produce outcomes.

The type of connectivity discussed in this dissertation needs to be distinguished from another kind, which has somewhat different practical and theoretical implications. As described in chapter 3, the increase in connectivity described in this study is conceptualized as an increase in network connectivity. Two new exchange networks are now important for the acequias: labor markets and water markets. This connectivity is slightly different from another perspective on connectivity that has been advanced by scholars studying the resilience of SESs. Within the panarchy framework (Gunderson and Holling 2002), increases in connectivity in a system are just one step in a periodic cycle (see figure 5.5). Here too, the increase in connectivity is seen as a process, and not an abrupt shock to the system. It is this increase in connectivity that leads to a more sudden change in the release phase. The paradigmatic example of this process is the build-up of biomass in forests. This increases the probability of forest fires, which release much of the built up potential energy.

The increase in connectivity in the acequias' case, however, seems to be importantly different than the connectivity as envisioned in the panarchy framework and illustrated by this ecological example. The incorporation of the acequias into a larger social and economic system is not part of any periodic cycle. Rather, it is one example of an unprecedented phenomenon that seems to be occurring around the world, where traditionally isolated social and ecological systems are now being affected by and brought into an increasingly large and globally interconnected economic system.

Despite this difference, perhaps one lesson we can learn from the panarchy framework is that it can be dangerous for a system to become over-connected. To return to the forest fire example, scholars and practitioners have learned that if periodic natural forest fires are suppressed, biomass builds up over time, which causes a fire to be much more destructive when it does occur. Similar findings have been found in highly connected networks, which are more vulnerable to cascading failures, when a local failure can propagate across a densely connected network. The paradigmatic example of is an electricity distribution system, where local failures shift the load to existing nodes, which in turn cause them to fail under the additional burden, and so on (Crucitti et al. 2004).

The lesson here is that the ramifications of the increase connectivity the acequias have experienced depend on the stability of the larger system. Chapter 3 emphasizes that the acequias are now vulnerable to the removal of this connectivity since they have lost much of their traditional knowledge with which they could support themselves without it. This makes them depend on the stability of this system which, if it becomes too connected, could itself become vulnerable to cascading failures[31]. This vulnerability may be ameliorated in the larger system, of which the acequias are now a part, if it can implement a modular network structure similar to that of the acequias themselves as discussed in chapter 2. This discussion reinforces a point I have already made, that scholars studying CPR management settings will need to increasingly incorporate properties of the larger systems into which local systems are becoming incorporated.

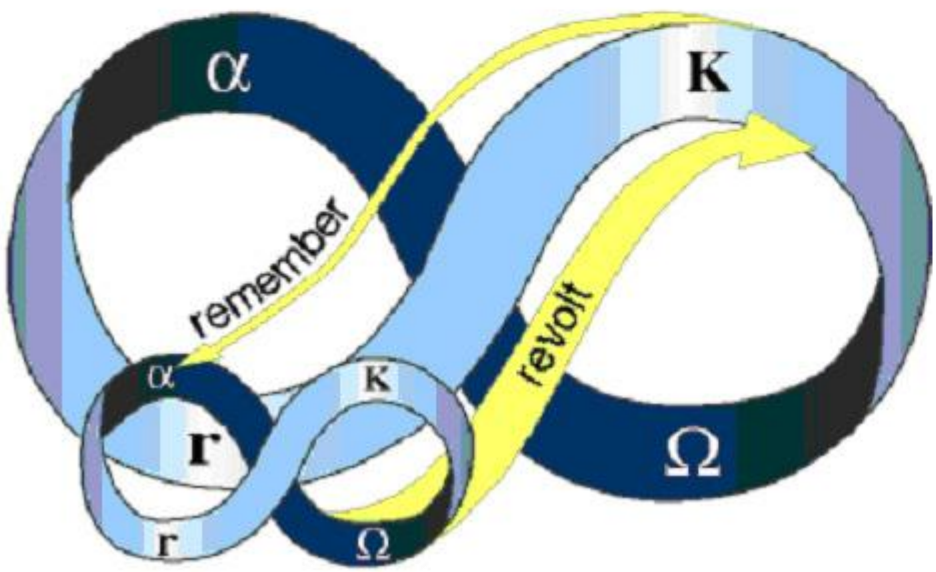

Figure 5.5: The panarchy adaptive cycle

To conclude, there are four conclusions I draw from this analysis regarding the direction that CPR management research could usefully take. First, it is important that commons scholars continue to increase the biophysical sophistication of their analyses. Secondly, it will likely be

[31] This is not a linear relationship; some connectivity is required for the existence of a network at all, and a certain amount is associated with network robustness (Dunne et al. 2002, 2004).

useful in many cases to adopt a structural (network) perspective in order to complement our social analyses and avail commons scholars of a rich set of concepts used in that literature.

The final two conclusions are related. First, we need to expand our analyses of resilience and vulnerabilities of community-based systems beyond one major dimension, by exploring how the relationships in their basins of attraction make them resilient or vulnerable along multiple dimensions. This will be facilitated by implementing the typology introduced in chapter 3. Finally, to the extent that many of these dimensions involve the influence of an external environment upon local systems, we need to move from primarily local-level analyses to ones that consider the social, political, and economic context in which localities are situated. This is particularly important in the modern, hyper-connected world in which communities find themselves. Traditional policy analysis has had problems with considering local-level heterogeneities. Scholars studying CPR management need to avoid extending themselves too far in the other direction.

5.6 Generalizability and diagnostics

The central framework used for this dissertation, particular in chapter 2 and this final chapter, is described in Ostrom (2007). There are two different purposes that such a framework can serve. First, it can be used to provide an analyst with the concepts and relationships he or she can use to better understand a case. In this sense its value is partly as a heuristic aid. This is the purpose that this framework has served in this study. The second purpose of such a framework is to facilitate cross-site comparison and general theory-building, once several empirical studies have been conducted using the same framework.

There a few additions I would make to the framework to improve its utility as a heuristic guide when applied in a particular study. These additions, however, are not fundamental and do not change the structure of the framework. They have been discussed in a previous section, where I addressed several additional variables that scholars studying community-based CPR management regimes might want to consider, such as network structures. The remainder of this section describes one change I believe could be made to the structure of the framework to improve its utility for cross-site comparison and theory-building. This change regards the scales and levels that are used in the framework.

Ostrom describes her framework as multi-tiered. I would describe it as multi-leveled and multi-scaled. Gibson et al. (2000, 218) define a scale as the “spatial, temporal, quantitative, or analytical dimensions used to measure and study any phenomenon”, and a level as “the units of analysis that are located at the same position on a scale”, such as days or square meters. Cash et al. (2006) adopt this terminology and elaborate: “’Cross-level’ interactions refers to interactions among levels within a scale, whereas “cross-scale means interactions across different scales, for example, between spatial domains and jurisdictions.” Someone might read Ostrom’s article and interpret her framework as crossing levels along a single scale. However, I believe it crosses several scales as well.

The first, or highest, level in Ostrom’s SES framework is the SES itself. The second level decomposes this system into six to eight components that constitute it. This decomposition reflects that fact that SESs are complex, hierarchical systems in the sense introduced by Herbert Simon (1995, 26), where he discussed nearly decomposable systems:

> *A familiar example is the molecule, composed of atoms which are composed of electrons and nuclei, which are composed of elementary particles, which are composed of quarks. Another example is the biological organism, which is composed of organs, which are composed of cells, which contain organelles, which are composed of molecules, and so on. A third example is human society, which is composed of economic, social, and religious organizations, these, in turn, of subgroups, down to the level of families. A social example is more complex than the others, since each individual may belong to a number of the larger subgroups-a family, a business firm, a church, and so on.*

Gibson et al. (2000) refer to such a nearly decomposable ordering, where subunits interact to form units, as a "constitutive hierarchy" (220). We might refer to this type of scale as structural/functional (as opposed to spatial or temporal, although there certainly are correlations between levels in structure/function and their spatial and temporal levels).

The second tier in Ostrom's framework does not continue along this hierarchy or scale by further decomposing these SES components into their respective components, but instead lists possible dimensions along which each of these components can vary quantitatively or qualitatively. For example, the users category, included in tier one as one of the essential components a SES, is not broken down into multiple possible sub-groups of users. Instead, properties of the users are listed, such as the total number of them, their dependence on the resource, or their geographic location. Similarly, the resource system, another second tier component of a SES, is mostly not broken down into its possible subcomponents (with the exception of RS4 – human constructed facilities). If tier two were consistent along the same structural-functional scale, it would list other components of the resource system, such as groundwater, surface-water, pasture, and arable land as part of the resource system in an irrigation system.

Therefore, Ostrom's second tier is not actually the third level down from the SES itself, because it is not along the same scale as the first two levels. What we need to do, I would argue, is to explicitly decompose the first tier components into their possible respective sub-components. Then, within each of these multiple levels along the constitutive hierarchy that structures a SES, we can specify the components and their relevant properties. This is essentially what Ostrom has done for the first tier. In this approach, what Ostrom calls the second tier would be a specification of the dimensions along which each of the first-tier components may vary, and not an additional level along the constitutional hierarchy. This approach also includes the possibility of defining different types or properties of the SES itself, which are not reducible to its components or their properties.

An argument could be made that this is an excessively onerous approach, and that it would be impractical to measure each of the properties of each of the components along multiple levels of a SES. This problem results in part from the fact that the degrees of freedom of the system's description rise non-linearly as we add further levels along a constitutive hierarchy. This is an important argument to consider. However, I believe that an important conclusion of this particular study is that this complexity can be simplified to enable a feasible analysis. The first reason this is possible is that not all of the components and their properties must be explored in order to understand a particular SES, as Ostrom notes. Secondly, this simplification results from the fact that the values of SES component variables are interdependent. This interdependence is important for two reasons: first, it is a finding in itself that helps us understand the system; second, it lowers the degrees of freedom in describing the system, and can greatly simplify its analysis.

These inter-dependencies can be either conceptual or causal. In the former case, two dimensions covary because they are measuring a similar phenomenon. An example of this in this study is the acequias' network centrality and the presence of leadership: leaders who provided public goods in the acequias are highly centralized in the users' networks of relationships, producing a network structure with an important level of centrality. Secondly, covariance may result from a causal relationship. This is the kind of covariance that statistical analyses such as those in chapter 4 attempt to uncover. Table 4.5 in chapter 4 presents a series of pair-wise correlations. An important example from this study is the negative correlation (-0.39) between water sharing agreements and groundwater availability, which suggests a causal mechanism: acequias with less access to groundwater have sought out other ways of supplementing regular surface water supplies in times of shortage.

Whatever the source of covariance and decrease in degrees of freedom, the significance for analysts is that when they tackle a particular component's properties, they are not starting from scratch. Instead, they can ask whether or not a particular component or variable is relevant at all, given what else they know about this system. This is a step-wise diagnostic approach, where questions asked of a system are based on previous knowledge gained about the system. Additionally, once they have decided that a component or a property of a component are relevant, they can approach it with a set of hypotheses regarding how these dimensions are likely to covary with others based on previous empirical analysis and established theory.

To conclude, I believe that while Ostrom's (2007) framework is quite useful as a heuristic guide for undertaking a particular empirical study of a SES, a few important changes could be made to make it internally consistent and more amenable to cross-site comparisons. These comparisons can in turn provide insights for building theory and for further improving the framework.

5.7 Policymaking and policy analysis

The primary implications this dissertation has for policy analysis are that policy should not remain as simple as it has under the market-state dichotomy, and that a range of important outcomes should be considered to augment the traditional goal of efficiency, particularly in the face of irreducible uncertainty. Such over-generalized analysis can lead to a kind of government failure described by Hayek (1945) and Scott (1998). This failure occurs when governments apply a blueprint set of policies to heterogeneous settings, resulting in mismatches between those policies and local social and environmental properties.

Addressing this problem will involve nested sets of governmental arrangements as described by Wilson (2002) and Young (2002). To do this, the path dependence associated with traditional arrangements will have to be overcome. An additional challenge that will need to be overcome will be obtaining sufficient amounts of data that are required in order to implement sophisticated social-biophysical analyses of SESs and explore their similarities and differences. This is likely to be extremely difficult in countries with few public resources to support such work. This study relied on public data produced by the state of New Mexico and the U.S. federal government that required extensive resources to produce. These data include Taos County assessor GIS data, the hydrographic survey maps produced by the New Mexico OSE, stream flow data provided by the USGS, and Landsat satellite images recently made freely available by the USGS.

It seems likely that in many other countries around the world, this data would not have been available and this study, as it is, would have been difficult to impossible for me to complete. To conclude, while I am encouraged by the relative success of implementing an interdisciplinary approach to the acequias in this dissertation, I believe that substantial challenges remain if we are to better establish a policy-relevant research program that conducts socially and biophysically sophisticated analyses across a diversity of settings in a way that facilitates comparison and theory building. As discussed in this final chapter, I do believe there are important steps that can be taken to tackle these challenges.

5.8 Future work

To conclude, I want to discuss the implications of this project for future research. There are two elements to this: first, a shift in perspective that this study embodies in research on community-based natural resource management. Second, I will discuss additional research on the acequias that could be done to strengthen the inferences made here.

This analysis represents a shift in the traditional perspective on community-based natural resource management. Traditionally, community-based natural resource systems are valued in the CPR literature for their ability to sustainably manage natural resources. Gradually, however, the emphasis has moved towards examining the factors that maintain these systems themselves, rather than the resource they govern. There have then been two related but distinct research questions that scholars have attempted to answer: first, how can we sustainably manage our natural resources? Second: how can community-based natural resource management systems persist? This research primarily addresses the second question, not the first.

It is somewhat more difficult to maintain the original perspective when studying community-based irrigation systems, as the sustainability of the appropriated resource, water, is often exogenous to local management practices. This does not mean that comparing different management regimes via some biophysical metric is not feasible, as it has been done (Lam 1998). While the acequias are seen as being resilient as measured via a biophysical estimate (NDVI), it is not their ability to sustainably manage a natural resource that is emphasized. Rather, the acequias, like many similar systems, are seen as having a value in themselves which should be maintained in the face of forces of globalization and economic integration (Rivera 1998).

Having adopted this perspective, my goal here is not to argue one way or the other about the intrinsic value of systems like the acequias, although I believe there are good arguments for why we should value them. These revolve around the problems associated with their integration into a larger system, such as hyper-connectivity or a lack of modularity of that larger system, and a loss of institutional diversity (Ostrom 2005). These issues apply to many systems similar to the acequias.

There are also some reasons for valuing the acequias that are specific to those in Taos and in other specific locations. As discussed in previous chapters, they can recharge shallow groundwater aquifers, where these are present, and can make important changes in stream hydrographs that ameliorate drought periods experienced downstream. As such, the Taos acequias do play an important role in sustaining the *groundwater resource*. This is in sharp contrast with the effects of urban land cover that has substantially replaced the acequias in Taos, which decreases percolation and increases surface run-off. Additionally, storing water in underwater aquifers decreases losses to evaporation that characterize large surface-water reservoirs that are extensively used in other parts of New Mexico and other southwestern states. As a result, I believe that the acequias could play an important role in a conjunctive water management regime throughout New Mexico (see Blomquist et al. 2004 for a discussion of conjunctive management in the southwest United States).

To conclude with the second component of this section, there are several avenues that could be explored in order to expand on the research that has been conducted so far and better support some of the inferences and conclusions I make. These mostly focus on the issue of eliminating alternative explanations for the story that has been told here. Important components to this story that have been left out include zoning laws in Taos County, which certainly affect the acequia communities. Additionally, property taxes can have particularly strong effects on impoverished farmers who are trying to maintain their historical culture while supporting themselves with relatively low-paying service jobs. This occurs in part because property taxes in Taos County can depend on the market value of the property itself (Vigil et al. 2009), which, in and around Taos, is likely to have dramatically increased in recent years due to rising demand from wealthy individuals. Anecdotal evidence suggests that there are many instances where farmers were priced out of historical farmland close to the town of Taos, and have had to move into mobile homes in the outskirts of the valley, which are easily visible throughout.

Another process that could be analyzed is the impact of agricultural markets on the acequias. These could affect the production of livestock and crops in the acequias through rising or falling prices. As mentioned in section 5.2.3., there is likely a suite of reasons for the declining livestock numbers in Taos valley. Population and demographic changes are a critical component. Less emphasized is the impact of agricultural markets, such as a decline in wool prices produced by the introduction of substitute goods based on more advanced technologies (NRC 2008).

Finally, the possibility that the acequias themselves may have inflicted harm on vegetation in the valley through overgrazing is not explicitly addressed in this study. This, in turn, could have been exacerbated by a loss of historically available common property high altitude grazing lands. To conclude, each of the reasons for the decline are related to an increase in connectivity between the acequias and their external environment, emphasizing the importance of this type of disturbance on the acequias, and on many systems like them.

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